# PROBLEMS IN ASTROPHYSICS

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PLATE I.

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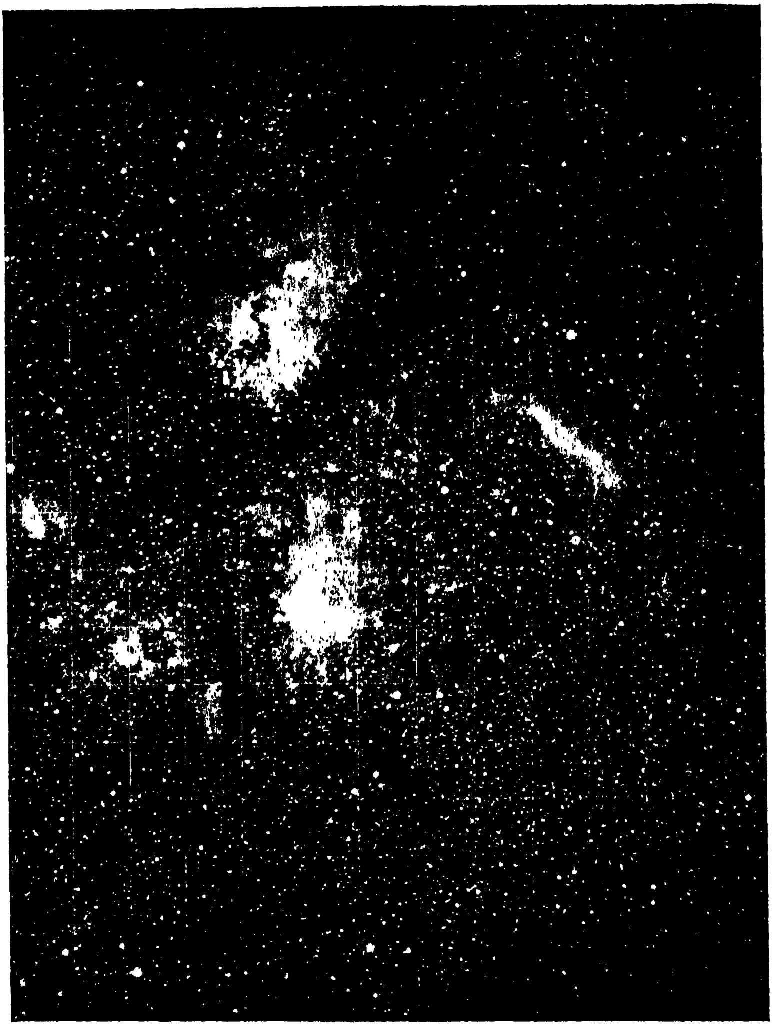

West.

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Photograph of the $\eta$ Argus Nebula. Taken by Sir David Gill in March 1892.
(*Knowledge*, vol. xvi. p. 70).

[*Frontispiece*.

# PROBLEMS

IN

# ASTROPHYSICS

BY

AGNES M. CLERKE

AUTHOR OF

'A HISTORY OF ASTRONOMY DURING THE NINETEENTH CENTURY,' 'THE SYSTEM OF THE STARS,' AND OTHER WORKS

'*In solidis et veris aspiramus ad ultima et summa.*"

Novum Organum, ii. 51.

CONTAINING 81 ILLUSTRATIONS

LONDON

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1903

THIS WORK IS DEDICATED

BY PERMISSION

TO

SIR DAVID GILL, K.C.B.

WHOSE SUGGESTION AND ENCOURAGEMENT PROMPTED ITS

COMPOSITION AND ANIMATED ITS PROGRESS

# PREFACE

THE object of the present work is not so much to instruct as to suggest. It represents a sort of reconnaissance, and embodies the information collected by scouts and skirmishers regarding practicable lines of advance and accessible points of attack, with a view to annexing for the realm of knowledge some further strips and corners from the territory of ignorance. Its inspiring motive, in short, is the desire for a rectification of the frontier in the interests of science. Material resources for the furtherance of such encroachments are not lacking. The globe is studded with observatories, variously and admirably equipped. Yet innumerable objects in the sidereal heavens remain neglected, mainly through inadvertence to the extraordinary interest of the questions pending with respect to them. In the following pages it has been sought to indicate some of these individually, and in their relations to the larger meanings of cosmical research. But this could be done effectually only from the vantage-ground of our actual acquirements; hence the book, although primarily designed to stimulate the progress of astrophysics, necessarily includes an account of its present state. Before attempting to add to our store of learning, we must realise what is already possessed.

The unknown, it is true, is indefinitely vast, and the rays of light which we can project into its darkness penetrate but a short way. Our programme of inquiry must accordingly be limited to what is now practicable, or promises to become

so in the immediate future. The unforeseen, too, will have something, perhaps much, to do with prescribing directions for fresh researches. Queries, in the coming years, will be put to the skies very different from those here propounded; and answers of a surprising kind will doubtless be afforded to our present interrogatory. The keen delight of such revelations will reward those who, loving truth for its own sake, have laboured for its promotion; and if these pages should, in any degree, help to quicken and guide their noble enthusiasm, they will have amply served their purpose.

They do not, however, cover the whole field of astrophysics. Planetary and cometary astronomy are deliberately, although for different reasons, excluded from treatment in them. The moon and planets still belong to the theoretical and descriptive departments of the elder celestial science. Nearly all that is known about their condition has been learned by direct telescopic observation. The items of information added through the aid of the camera and the spectroscope, though valuable, are very few. The orbital characteristics, on the other hand, of comets and meteors are too prominent to be set aside in any profitable discussion of their nature. They are of the very essence of the phenomena; yet they would be out of place in a book strictly limited to the consideration of the heavenly bodies under their physical aspect.

The writer has received much courteous help from various quarters in preparing the illustrations, and desires in particular to acknowledge her obligations to Sir William and Lady Huggins, to Sir David Gill, to Dr. Roberts, F.R.S., to the Rev. W. Sidgreaves, S.J., Mr. W. E. Wilson, F.R.S., M. Deslandres, Professor Hale, Professor Barnard, to Professors E. C. and W. H. Pickering, and to Professor Campbell.

LONDON, *December* 1902.

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# INTRODUCTION.

## RISE AND SCOPE OF ASTROPHYSICS.

THE astronomy of the ancients was purely formal. It did not profess to look beyond appearances. Its aim was reached, provided that phenomena were—in the old Greek phrase—mathematically "saved," at whatever cost of material impossibility. Kepler first speculated on the causes of celestial movements, and introduced the term "physical astronomy" with a full sense of what it implied. Its establishment as an effective branch of knowledge was a prime desideratum with Francis Bacon. While rejecting the Copernican system and ignoring Kepler's laws, he aspired towards a science of the skies that should be no simulacrum, like the "stuffed ox of Prometheus," but should have in it the breath of life and the instinct of progress.[1] Anticipating with imaginative insight the prosecution of researches which Comte, two centuries later, declared to be, in the nature of things, futile, he broadly laid down the lines of a new astronomy, indistinguishable from modern astrophysics. As the province of this "philosophy" of the heavenly bodies, he assigned inquiries into the nature of their substance, of their qualities, properties, and influences, as well as into the source of the motive power acting upon them. Vitalised, as it were, by contact with mother-earth, it was destined in his prevision to a community of advance with terrestrial science, one imparting to the other novel truths tending to mutual profit and simultaneous

[1] Fowler, Introduction to *Novum Organum*, p. 38; *Descriptio Globi Intellectualis*, chaps. v., vii.; *De Augmentis*, iii. 4.

development. Thus the long-divorced sublunary and translunary worlds were conjoined, and their material unity—the essential principle of astrophysics—was definitively proclaimed. This daring forecast transcended the scope even of Newton's discovery, and left Kepler's prescience far behind. For Kepler, as an astronomer *ex professo*, took full account of apparent impossibilities, while Bacon's was "the golden guess"—

> That's morning star to the full round of truth.

Yet it might have been derided as that of an uninformed amateur. It rose indeed out of sight of ordinary minds.

The establishment of the law of gravity was the first step towards its realisation. Thereby the terrestrial regimen was, in part, extended to the skies. The moon assumed the aspect of a projectile in perpetual flight, tangentially launched *ab initio*, and hence keeping its distance from the earth, while the planets, including our own globe, proved to be similarly related to the sun. Thus celestial movements lost the mystical character long ignorantly attributed to them, and were found to own a common cause with movements at the surface of the earth. They became predictable, since the cause acts uniformly and simply; theoretical astronomy, with practical astronomy at hand to provide its raw materials and test its results, took rank as the most perfect of the sciences; the idea of a definable force put to the rout the old vague notions of "tendencies," "appetites," "passions," or "potencies," and a dynamical was substituted for a merely kinematical system.

Gravity, however, is a force of the utmost generality in the way it affects matter. It takes no notice of distinctions of kind or quality. The substances acted upon may be hot or cold, dense or rare, elementary or compound; they may be of any imaginable chemical or mineralogical constitution; they may be in any state of aggregation; they may be organic or inorganic; no difference is perceptible; gravity is concerned solely with mass, and is measured strictly by movement; and from gravitational inquiries, accordingly, mass and movement can alone be learned. So far, then, only one principle of unification was introduced. One fundamental property of matter was known from 1687 to belong equally to the earth

and planets; and Herschel's discovery in 1802 of mutually revolving stars virtually made the "writ to run" throughout the sidereal world as well. The universality of an apparent mass-attraction was a great fact, but seemed destined to remain isolated; for Olbers's "electrical theory" of comets amounted to no more than a suggestive speculation. Then in 1852 the triple identification by Sabine, Wolf, and Gautier of the sun-spot and terrestrial magnetic periods showed the reality of solar influences exercised in a manner not easy to apprehend, but capable of being brought to the test of experimental investigation. Cosmical physics began to separate out and take recognisable shape. The spring of its most rapid growth, however, lay in another direction.

The discovery (in Professor Keeler's words[1]) "that the light which reveals to us the existence of the heavenly bodies also bears the secret of their constitution and physical condition," afforded a solid basis for a science of far-reaching import. "The spectroscope placed new and hitherto undreamt-of powers in the hands of men. It is to the astrophysicist what the graduated circle and the telescope are to the astronomer." Observations of the heavenly bodies by means of their *analysed* light came to the aid of observations through their *integrated* light. Their radiations, visible and invisible, were brought within the range of detailed study.

Of study, not only visual, but photographic. The sensitive plate has three leading prerogatives. It *sees* where the eye is blind; its impressions are cumulative to an indefinite extent; they are permanent; they constitute documentary evidence of incontestable validity, which can be produced or referred to at pleasure. Spectroscopic photography, or "spectrography," dates from Sir William Huggins's adoption of the dry gelatine process in 1876; and his discovery, three years later, of the ultra-violet series of hydrogen-lines in stellar spectra started it on its career amid acclamations. Nor has the promise been belied. The efficiency of the camera is of so high an order that direct visual observations of prismatic light are now only by exception made. This is perhaps unfortunate, since the two kinds of results are, to some extent, supplementary, and can often be most usefully compared and

[1] *Astrophysical Journal*, vol. vi. p. 273.

correlated. The superiority of the chemical method, however, is nowhere more conspicuous than in the motion department of the new astronomy. Its powers in this direction were tested with striking success by Vogel in 1888, and their development, rapid as it has been, does not seem to be near its term. The determination of radial velocities through changes in the refrangibility of light emanating from the bodies actuated by them, has made astrophysicists free of a territory which belongs equally to the domain of traditionally equipped astronomers. Here we get back to elementary facts of mass and motion, ascertained, however, not *frontally* by measures of position, but *strategically* by inference from radiative modifications. They are, indeed, of a nature unaffected by position, and hence undiscernible with the micrometer. A body shown spectroscopically to be in swift movement might be absolutely immobile telescopically; or the conditions might be inverted, each method taking cognisance of only one component of the total velocity. An immense extension was accordingly given to the field of research in sidereal dynamics by the application, through Sir William Huggins's initiative, of "Doppler's principle." It supplied not alone the means of completing investigations which could otherwise be pursued only in a one-sided manner, but of setting on foot entirely new ones of incalculable significance. Thus the rate of the solar translation through space, valued little better than conjecturally from the *proper*, or thwartwise motions of the stars, can be derived securely and at once from their *radial* motions. Of the movements of nebulæ nothing is known—and very little is likely to become known for some centuries yet to come—except through spectroscopic measurements; for they are so remote that their positions change with extreme slowness, while the evidence of radial speed is tendered immediately, without regard either to time or distance. But the most curious discoveries afforded by it are of double stars revolving in such close contiguity as to be permanently inaccessible to telescopic observation. And these are precisely the systems of highest cosmogonic interest, as being, most likely, at the outset of their evolutionary careers. They are surprisingly numerous, and will doubtless prove to be linked on to tele-

scopic binaries by an uninterrupted succession of couples farther and farther apart.

This common ground of the two astronomies, where motion in the line of sight is the object of research, has already proved fruitful of varied novelties, and its yield is not within view of being exhausted. It could, however, never have been worked to advantage but for the timely assistance of photography. The living retina is here conspicuously inferior to the chemical retina; for aerial disturbances are eminently baffling to eye-estimates of line-shiftings, while the sensitive plate, ignoring momentary fluctuations, records true mean positions. Visual measures are hence rarely trustworthy; advantageous occasions for securing them are few; so that they must always be either poor in quality or scant in quantity; and accumulated data are needed as the bases of systematic inquiries. The use of the camera is accordingly indispensable, and has become all but exclusive.

Astrophysics widens in scope year by year, and as it wins *extension* it gains *intension*, each advance carrying it deeper into the secrets of nature. Towards this result the alliance with photography has contributed with signal effectiveness. The impersonal method confers a certainty and power in dealing with obscure phenomena which can only in special cases be claimed for the eye. Moreover, it is of larger application. It can be employed on an expanded scale both of time and space. It is thus the fittest means for collecting statistics of the heavens; and statistics are urgently in demand for the ultimate purposes of celestial science. The whole future of astronomy has indeed come to depend upon the validity of photographic evidence, and specialties of manipulation and development, the idiosyncrasies of variously prepared plates, the shrinkage of gelatine films, the effects of graduated exposures, have to be studied no less diligently than the theories and errors of brass and glass instruments where immediate determinations of celestial situations are in question. Astrophotography is an art, and has a technique of its own needing labour for its mastery.

The ramifications of astrophysics are numerous and intricate. To trace them out in detail would be to unroll an elaborate chart of the sciences. Celestial chemistry is in

itself an all but limitless department. It includes terrestrial chemistry, thermotics, thermo-electricity, and slides inevitably into the wonderland of molecular physics and ethereal powers and qualities. For the interpretation of spectra demands acquaintance with the nature of the vibrating systems originating them, with their relations to "imponderable" agencies, with their perturbations, modifications, and disruptions under the stress of circumstances at present scarcely definable. Here there are worlds to conquer. One phase of these inquiries is marked by the recognition of harmonic line-series in the spectra of the chemical elements. Another by the discovery that wave-length is a function of density, that an increase of pressure slightly shifts the rays emitted by a glowing vapour downward towards the red. A third, still more significantly, by the "Zeeman effect," with its barely conjectured implications. It consists in the distension and subdivision of lines normally slender and single, when the radiation takes place in a strong magnetic field; and the specification of the laws of its production, whether close at hand under controlled conditions, or far out of reach at the surface of celestial spheres, allures the imagination with possibilities of far-reaching consequence. Above all, there seems to be a reasonable chance of learning from it something about the electrical state of the stars. The relative strength and brilliancy, moreover, of spectral lines afford criteria of temperature, density, and modes of electrical action, but not with satisfactory explicitness. There is much difficulty in duly apportioning the effects. Thermal and electrical conditions are rarely separable; degrees of density and of temperature again need very careful discrimination. Electricity is the indispensable agent for exciting luminosity; precisely, however, what part it reserves for itself in the matter—whether heat, as generally assumed, is its plenipotentiary, or merely a delegate with limited powers—is, so far, unknown. Nor is it easy to define what takes place in the path of the discharge, yet it is from the carrying molecules only that the light examined is derived, and it is their state only that is indicated by its peculiarities. Still, beginnings have been made in the experimental disentanglement of this web of interdependent operations, and specific inferences of value

regarding the heavenly bodies have already been drawn from some preliminary ordering of the various classes of facts.

The rotation of the heavenly bodies is a department annexed, while their chemistry has been created by the new astronomy. No longer treated as a simple geometrical datum, it is studied as an index to their physical constitution. Spectroscopic observations of axial movements in the sun and planets are among the most delicate and curious that have been made. They may possibly be extended to stars, nebulæ, and comets, but the prospects here are dubious. Nor has the old direct mode of determining rotation been superseded by the novel method. Its employment, in some cases supplementary, is rendered in others, by the force of circumstances, exclusive.

Moreover, nearly the whole "descriptive" section of astronomy is embraced by astrophysics. It is now extensively yet not altogether worked by photographic means. The camera has so far succeeded very imperfectly in depicting planetary surfaces; but the required special conditions are being carefully studied, and will perhaps before long be realised. The difficulties attending lunar photography have of late been, in the main, overcome, as the magnificent Paris and Lick Atlases of the moon testify. They nevertheless record essentially what was known before; they elucidate no perplexity; selenology has been adorned and illustrated, but not greatly promoted by their compilation. The self-portrayal of recent comets, on the other hand, has been accompanied by remarkable disclosures. They need, however, skilled interpretation, and experts in this branch are to seek. The pictures are there, full of rapidly changing and significant detail; yet patience must be exercised before we can read in explicit terms what they implicitly convey regarding the constitution of the bodies they represent.

The photographic study of the Milky Way—pursued systematically by Professor Barnard—has been more definitely and distinctly communicative. For his plates not only bring clearly to view the mixed stellar and nebulous nature of that gigantic assemblage, but also afford grounds for inferences of great moment as to the general distribution of the stars.

This indeed is a subject which might seem expressly reserved for treatment by the older astronomy. Yet the all-pervasive physics of the skies has a lien upon it. Spectroscopic considerations come into play. The modes of stellar scattering in space are different for the various stellar types, and the connection suggests queries, not readily answered, regarding the origin of those types, and the very genesis of the sidereal system itself. Abysses of speculation open before us as we contemplate the surging galactic cloud-forms depicted through the simple instrumentality of a portrait-lens and a sensitive-plate.

In the photometric branch of astronomy there is a similar concurrence of claims. The arrangement of the stars in light-ranks serves primarily as a test of their arrangement in space; the test, however, is illusory unless the nature of their spectra be taken into account. Again, while measurements of the brightness of individual stars are essentially physical in their import, they are also carried out for the geometrical purpose of determining occultation-phases. The photometric observation of the eclipses of Jupiter's satellites is a corresponding example in the solar system. Otherwise, in its varied applications to the sun and moon, to planets, asteroids, and comets, photometry may be said to have purely physical aims. These have to do, not only with integral, but also with analysed light. The "spectrometric" division of photometry consists in the comparative estimation of ray-intensities, in balancing one against another the differently refrangible beams from a given source of luminosity, in constructing, that is to say, its spectral energy-curve. In both departments the camera proves an invaluable ally. Photographic photometry occupies, indeed, a place apart among the arts and crafts of astronomy. It has its own laws, its own problems, its own difficulties, and it furnishes data which can be interpreted on principles valid for them alone.

The specialties of solar physics are too numerous to be particularised. Among stars, perhaps an insignificant star, the sun is nevertheless by its comparative vicinity to ourselves brought within range of a whole series of observations impracticable elsewhere. In solar research, accordingly, novel devices abound; such as the "double-slit method," so

happily availed of by Hale and Deslandres for the spectrographic portrayal of "flames," facular and chromospheric. The complex operations conducted under shelter of eclipse are equally peculiar in their objects and in their system; by them only is the unique problem of the corona at present accessible to attack; that of the "reversing layer" is even more elusive in its momentary presentations. Sun-spots, on the contrary, are open to leisurely daylight inspection; yet the perplexities connected with their structure and spectra grow rather more than less acute as facilities for their scrutiny are increased. But this is no uncommon experience in the arduous walks of science.

The pliancy and generality of astrophysics contrasts singularly with the austere exclusiveness of gravitational astronomy. The new mode of celestial inquiry follows every indication, lays hold of every clue; it promises much, it often performs more; yet its advance is at times hampered by the very circumstances which make it brilliant and surprising. For it "deals," as Professor Mendenhall said in 1892,[1] "with a matter of many properties, some of which are but little understood. While its conclusions are of vital importance and of intense interest, they result from deductions in which the premisses are insufficient, and are proportionately uncertain. The new astronomy must for a long time abound in contradictions and controversies, until, and largely through its development, we shall possess a knowledge of the properties of matter when subjected to conditions differing enormously from those with which we are now quite familiar."

Here indeed lies the fundamental peril, and at the same time the essential prerogative of astrophysics. Its concern is with phenomena falling partly within, partly without the range of ordinary experience. It has to do with matter in transcendental states. Hence the necessity for having recourse to the risky expedient of "extrapolation"—that is, of applying unrestrictedly to the unknown, rules gathered from observation over a comparatively narrow area. The indefinite continuity of natural laws is assumed by it, but certainly on no sufficient warrant. There is indeed no help; no other means are available; the line and plummet that have

[1] *The Observatory*, vol. xx. p. 144.

proved serviceable for sounding the estuary must be used likewise for the ocean. The upshot, however, is merely a "first approximation," to be subsequently corrected and controlled. And it may be of immense importance as an index to consequences or possibilities which could not have been foretold, and defy even imaginative realisation. But just here resides the exploring faculty of astrophysics. It often acts as the pioneer of terrestrial science. "The discovery of unknown laws" (in Professor Keeler's words), "as well as the explanation of phenomena by laws already known, is one of its most important objects."

A great future is reserved for it. It postulates a law of order, the same always and everywhere, and its primary function is to verify that postulate, step by step, point by point, under continually widening horizons of knowledge. There is no such thing as chaos, it tacitly asserts, in the sidereal world or outside of it. For chaos is the negation of law, and law is the expression of the Will of God.

# PART I

## PROBLEMS IN SOLAR PHYSICS

# CHAPTER I.

## PROGRESS OF SOLAR PHYSICS.

SOLAR Physics is the science of the sun as an individual body. It is not concerned with the sun as the ruler of the planetary system, or as a member of the sidereal system. The questions which it seeks to answer relate exclusively to the "thing in itself." And these questions, through the effectiveness of modern methods, have become *answerable.* Few of them, it is true, have yet been *answered*, and all can never be set at rest, since each reply marks only the starting-point for a fresh interrogatory. This must be so; the prospect inevitably widens with the attainment of a higher point of view. Nor is it likely that the ascent will soon terminate. It is indeed towards a summit cloud-wrapt and self-withdrawn. The essential point, however, is that stagnation has given way to progress, surmise to inquiry, and barren wonder to stimulating curiosity.

Solar research made a threefold start about the middle of the last century. First came Schwabe's discovery of a decennial sun-spot period, followed up by Sabine's announcement of a coincident terrestrial-magnetic period. Then, in 1860, Kirchhoff published his momentous chemical interpretation of the Fraunhofer lines, showing the presence of familiar metals as glowing vapours in the sun's atmosphere. Finally, on 18th July of the same year, the "red prominences" were photographically referred to their true location, and the whole marvellous eclipse-garniture was at once annexed to the domain of solar physics. The investigations corresponding to these three beginnings were pursued at very unequal rates of advance, and with considerable disparity of success. The

chief triumphs were those of the prismatic method. From the spectroscope single-handed, the old order of ideas received its death-blow. Glaring incongruities notwithstanding, it might have survived a couple of decades longer had it not been for the reading of the strange Fraunhofer inscription. But the subversive effect of the attack delivered in 1860 was too palpable to be ignored. At last, unmistakably, the Herschelian theory of the sun was in ruins, and it only remained to clear away the rubbish of the structure preparatory to erecting a modern edifice on new foundations.

Its corner-stone was the principle of the conservation of energy. This obtained its first solar application from Helmholtz in 1853. His gravitational hypothesis explained the enormous outflow of heat from the focal hearth of the planetary household with a directness and simplicity that compelled conviction of its truth. Energy of position is, in this view, the store drawn upon by radiation; and it is a store so vast that millenniums of thermal expenditure will make no perceptible encroachment upon it. As the great globe cools, it contracts; and each one of its constituent particles falls, day by day, infinitesimally nearer to the centre, heat being thus mechanically evolved. Potential energy is in this way converted into actual energy, and we are warmed and lighted because the sun shrinks, and is raised by shrinkage to a surpassing pitch of incandescence. His constitution must then be such as to meet these requirements. For an ideal body, endowed at pleasure with fanciful properties, a machine has to be substituted, definitely adapted to the fulfilment of a recognised function. This change in the point of view is characteristic of astrophysical aims. It makes all the difference between antique and modern science. A great deal is involved in it. The demands of the novel situation are multitudinous, and can be met, not by speculative efforts, but only by toilsome experimental comparisons. These will need time and much patience, and can never be wholly satisfactory in view of the contrast between terrestrial and solar conditions. Yet the efforts towards their assimilation, unremittingly prompted by the new astronomy, lead to a continual growth of knowledge, and are unlikely to be relaxed until the torch has finally dropped from human hands.

The absence, then, of a satisfactory all-round theory of the sun need not be taken as an implication of failure. On the contrary, progress is necessarily attended by incompleteness. Facts, when research is most active and successful, accumulate too rapidly to be at once collocated. Finality means stagnation. Compare the map of the world drawn by Hecataeus with that by Herodotus. The earlier is by far the more finished production. Neat and trim, with its circumfluent Ocean Stream, it pictured the earth mainly from ideas of what it ought to be. The later chart, on the other hand, as the upshot of wider experience, admitted ignorance by abolishing limits and leaving room for the unknown. A true theory must always be somewhat expansible. It must be capable of accommodating new facts. Otherwise their intrusion will speedily rive it asunder.

Only the broad lines of solar theory can then at present be laid down. Details must be filled in gradually with the progress of research. The preliminary ideas, however, already acquired are unlikely to be subverted; we can represent to ourselves a sun which is a reality, and no figment of the brain.

Our luminary is neither solid nor liquid. It is mainly, perhaps entirely, gaseous; but its gaseity is of the "critical" kind, due to the combination of intense heat with enormous pressure. The thermal supplies needed to meet its vast emissive expenditure must be continually and rapidly brought from the central parts to the surface; and this can only be accomplished by the actual transport of the heated materials, conductive processes being much too slow to meet the exigencies of the situation. We thus recognise in the sun a globe riddled with convection-currents, of which the shining cloud-shell of the photosphere constitutes the limit. At the photospheric level the uprushing torrents deliver their cargo of radiative energy, and from the photospheric level the corresponding subsidence of cooled matter starts for the unimaginable furnace below. This course of exchange, however, must be greatly complicated by the rotation of the plastic mass in which it progresses. A true vertical circulation is rendered by it impossible; the ascending and descending currents must be variously and incalculably deflected.

Incalculably, since the state of the sun's interior lies, in some respects, beyond the range even of conjecture.

The very remarkable circumstance has been emphasised by recent inquiries that the photosphere fixes a boundary between two solar regions scarcely less strongly contrasted—to speak illustratively—than the terraqueous globe and its encompassing atmosphere. The sun has several distinct envelopes, but none, apparently, in the condition of atmospheric equilibrium. There is first a shallow, veil-like covering by which the disc is reddened and darkened. Next comes the "reversing layer," a bed of mixed incandescent vapours, some hundreds of miles in thickness, the absorptive action of which mainly produces the dusky lines in the Fraunhofer spectrum. It is overlaid, to a depth of four or five thousand miles, by the chromosphere, a gaseous ocean incarnadined by the crimson blaze of hydrogen. The irregularities of its outline develop, locally and temporarily, into "prominences," often of gigantic size, but belonging to the chromosphere as essentially as mounting waves and tossed spray do to the ocean. Finally, we reach the far-spreading corona, a mere lustrous phantom, approaching the absolute zero of density, yet of astounding decorative effect during total eclipses. Between the corona and the chromosphere there seems to be absolutely no material continuity, although structural relationships have been traced.

These appendages are distinguished by two peculiarities, rendered more obvious at each step forward in research. The first is that they contain an extremely small quantity of matter. The second, that the effect of the sun's gravity upon them is, in some way, neutralised. We have only to consider that at an elevation of three and a half miles air is reduced to one-half its sea-level density, while the corresponding height at the surface of the sun—where gravity is twenty-eight times more powerful than it is on the earth—is but one-eighth of a mile. Into the compass of a shell just one furlong thick, accordingly, half the substance of the reversing layer, chromosphere, and corona should be compressed, if the sway of gravity over them were undisputed. Its comparative impotence is attested not only by their vast extent and excessively slow rate of luminous degradation, but still more emphatically

by the almost total absence from them of spectroscopic symptoms of internal compression.

The various "claims" into which the wide field of solar physics has inevitably come to be divided are marked by curious differences of productiveness. Some are thickly sown with "pockets" of bright ore; others have hitherto yielded little beyond the "sparkle of golden splendour" on the surface. Thus the geometrical relations of sun-spots are not now more surely known than in the days of Derham and Cassini. A consensus of opinion that lasted a full century has given way to notorious disagreement. The elementary question as to whether spot-umbræ are elevations or excavations, is once more actively debated. True, the overthrow of an artificial unanimity often preludes a forward movement; yet it might have been expected that the immense mass of photographic records accumulated during thirty years would have amply sufficed to settle this matter once for all. It must indeed be admitted that direct sun-pictures, notwithstanding the exquisite perfection to which the art of taking them has been brought, and the striking nature of the details they often exhibit, have contributed only in a minor degree to the promotion of definite knowledge. Super-eminent among them are the long series due to M. Janssen's skill; yet after twenty years the *réseau photosphérique*, a phenomenon of "blurring" manifested by their means, continues enigmatic as to its nature, and open to doubt even as to its solar origin.

The swiftest advances in solar physics have been along the various routes opened by light-analysis. Four of these are broadly separated by differences of aim and method. The inquiries they have made practicable relate to the chemistry of the sun itself, the daylight study of prominences and faculæ through a selected element of their emissions, to radial movements in the sun, and to spectroscopic disclosures during eclipses. The Fraunhofer spectrum has been studied year by year with minuter accuracy, and similar refinements in the treatment of the arc-spectra compared with it have assured real, and annulled fictitious correspondences, largely, as may readily be imagined, through photographic agency. Spectra, to be exactly collated, must be durably imprinted. The fine measurements now executed upon them would be an

impossible task for the eye. Professor Rowland's invention of concave gratings in 1883 has also contributed very notably to the development of solar chemistry. They simultaneously focus impinging rays and disperse by diffracting them. No lens needs to be interposed, and thus the disturbing effects of selective absorption and unequal deviation are avoided. Improvements in the technical processes of photography—the substitution of gelatine for collodion as the vehicle of the decomposable salt; the intensification of sensitiveness in plates; modifications in their colour-susceptibility—have been equally essential. Mechanical contrivance has not been behindhand. Without faultless screws, for instance, there could be no perfectly ruled gratings. The chemistry of the sun has indeed drawn upon many and unexpected resources for its promotion.

Spectroscopic work at the sun's edge was carried on steadily for twenty-three years after its initiation in 1868. Its outcome was the collection of a mass of valuable information regarding the chromosphere and its jutting eminences. Their forms, movements, and duration were registered, the law of their distribution was ascertained, the mode of their conformity to the spot-cycle inferred. So rich a harvest was, in fact, gathered at once that the soil began to show signs of exhaustion; the prospect seemed dim of detecting any further essential novelties in this direction; the routine task of daily promenading the slit of the spectroscope round the limb lost its zest. Then in 1891 a novel commencement was made, and made in duplicate by Professor Hale at Chicago and M. Deslandres in Paris. They transferred the business from the eye to the sensitive plate, definitively and with splendid success. The photography of prominences, although tried on a correct principle by Professor Young in 1870, remained in an abortive experimental stage until recourse was had to the device of isolating the K-line of calcium, and depicting them in this single element of their light. It proved applicable to faculæ as well, and in one minute a complete picture of the disc and its appurtenances, as shown in the violet ray profusely emitted by them, can be secured with the spectroheliograph whenever the sun shines on either side of the Atlantic. The very name—"spectroheliograph"—of the instrument invented for the purpose comprises a history of changing

methods—of the supersession by photography of eye-and-hand delineation, and of the replacement in turn of direct photographic portrayal by impressions of spectral images. And there has been a corresponding modification of ideas. New conceptions are gaining ground, not through the broaching of startling theories, but under the steady guidance of undeniable, and often surprising facts.

Doppler's principle was applied by Sir Norman Lockyer about 1870 to *meteorological* investigations (as they might be called) in the sun. They disclosed the not infrequent occurrence there of portentous cyclonic agitations. Distortions and displacements of the hydrogen lines attested the rushing of incandescent whirlwinds at speeds up to 250 miles a second. Much has yet to be learned regarding these extraordinary phenomena, their relationships having scarcely received the detailed and particular attention that they deserve. Professor Young's use of the same method in 1876 to measure the solar rate of rotation served both as a test of its validity, which it established beyond cavil, and as a prelude to important refinements in the treatment of that intricate subject. Notwithstanding its anomalous retardation north and south from the equator, M. Dunér obtained in 1887-9 spectroscopic evidence of axial movement up to fifteen degrees from either pole, and thereby brought a widened range of its complexities under observational control. Line-displacements, too, similarly produced, have become the standard criterion for discriminating between the genuine solar, and the merely telluric constituents of the Fraunhofer spectrum; and it need scarcely be pointed out that to set them decisively apart is a pre-requisite to solar chemical progress.

Each favourable eclipse since 1842 has furnished to science its quota of new facts and inspiring suggestions. In 1851, the solar status of the "sierra" and "red protuberances," demonstrated in 1860, was recognised by all except a few obstinate sceptics. In 1868, the hydrogen and helium spectrum of these wonderful objects came into view; in 1869, the green coronal ray was detected. Then on 22nd December 1870, Young's tangential slit was momentarily lit up by the "flash spectrum" of the reversing layer, which, after twenty-six years, was photographically captured by Shackleton, and

so became the subject of definite and critical investigation. This was greatly promoted by the multiplied records of it obtained along the line of totality which crossed India, 22nd January 1898. The cyclical variation of coronal types, indicated by the substitution of luminous "wings" for the more familiar "glory," during the Rocky Mountains eclipse of 29th July 1878, was verified by a splendid series of coronal photographs taken in Egypt in 1882, at the Caroline Islands and Grenada in 1883 and 1886, in California and at Cayenne during the January and December totalities of 1889, at Novaya Zemlya in 1896, in the Deccan in 1898, in Sumatra and Mauritius in 1901. Sir William Huggins's device for photographing the corona in daylight, invented under the stimulus of the Nile-eclipse disclosures, unfortunately remains in abeyance. Its realisation is a prime desideratum in solar physics.

The progress of science in this branch might with substantial accuracy be described in the condensed statement that a fabulous luminary has made way for a working machine—a machine, it is true, of infinite complexity, yet in touch with, although transcending, the common order of things. Just here reside the extreme interest and value of such inquiries. They deal with what is concrete; they can be pushed on by experiment, but by experiment always straining to widen its resources. Limits are accordingly pushed back little by little—limits of temperature, of rarefaction, of ethereal stress as manifested by electric and magnetic intensity. The end of the process is not within view. The way, arduous though it be, lies open, and is securely travelled by those who, relying on the unity and continuity of nature, confidently hope to attain by it to the knowledge of higher truths.

# CHAPTER II.

## THE CHEMISTRY OF THE SUN.

KNOWLEDGE of solar chemistry is based exclusively upon the analysis of solar light. It advances *pari passu* with the interpretation of the Fraunhofer lines. And by their interpretation is signified the process of identifying them, one by one, with the rays of known substances, made to glow artificially in the laboratory. They are the characters of a script in the main decipherable, and already, to a satisfactory extent, deciphered. Their reversal from bright to dark simply implies that the prismatic background upon which they are projected represents a hotter source of radiation than theirs. In other words, the temperature of the photosphere is above that of the ignited vapours through which its light is sifted, and by which it is selectively absorbed.

Fraunhofer's survey of the solar spectrum was necessarily confined to its visible section, and was executed with very imperfect appliances. Yet the lines laid down in his map had the importance of permanent landmarks. The following is a list of the chief among them, their wave-lengths on Rowland's scale, and the chemical origins ascertained for them, being added:—

| Designation. | Wave-length in ten-millionths of a millimetre. | Origin. |
|---|---|---|
| A | 7594·059 (upper edge of a band) | Terrestrial oxygen |
| B | 6867·461 ,, ,, | ,, ,, |
| C | 6563·054 | Hydrogen |
| $D_1$ | 5896·156 | Sodium |
| $D_2$ | 5890·182 | ,, |
| $E_1$ | 5270·495 | Iron |
| $b_1$ | 5183·792 | Magnesium |
| F | 4861·496 | Hydrogen |
| G | 4308·034 | Iron |
| H | 3968·620 | Calcium |
| K | 3933·809 | ,, |

The first and last lines in this table approximately define the range of dispersed sunlight visible to ordinary eyes. It extends over nearly an octave; and a higher half-octave in the ultra-violet is disclosed photographically. The infra-red, however, offers a far vaster scope for exploration. Using a "bolographic" method, in which the camera registers what the bolometer[1] *feels*, Professor Langley has surveyed a stretch of dark radiations eight times longer than the bright strip mapped by Fraunhofer; nor was his advance downward in the spectrum checked by any insurmountable barrier. There is, indeed, much probability that long heat-waves and short "Hertzian" waves are really indistinguishable, and that the luminous spectrum passes without a break through the thermal into the electric spectrum.

In the ultra-violet region, on the other hand, a peremptory stop is put to research by the interposition of the air. It excludes by absorbing ether-waves shorter than about $\lambda$ 2950. Cornu found sunlight to be arrested just at this point. Sir William Huggins fixed the limit for the photographic spectrum of Vega ($\alpha$ Lyrae) at $\lambda$ 2970.[2] It does not fluctuate with meteorological conditions. Dampness and drought are equally ineffective in shifting the atmospheric barrier against the entry of quick vibrations. Cornu ascertained in 1881[3] that it is affected only by the height of the barometer. Nor is the reduction of impermeability through ascent above the earth's surface nearly as great as it would be if aqueous vapour were the producing agent. That oxygen is chiefly concerned is rendered certain by converging proofs. Nitrogen seems to be, in this respect as in others, nearly inert.

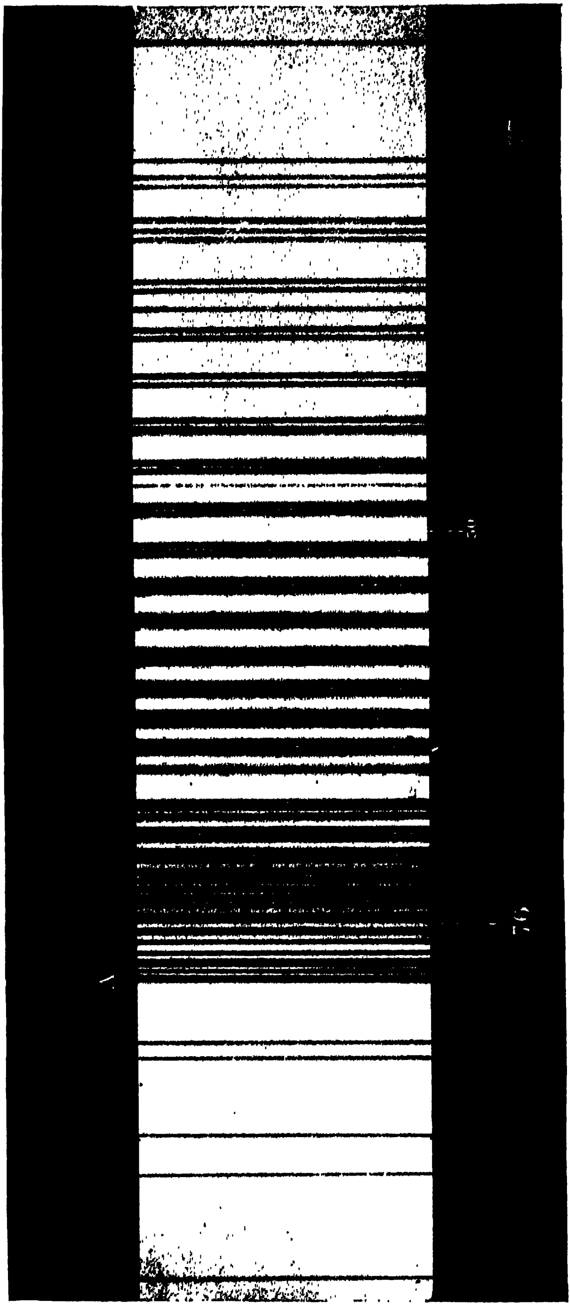
The general enfeeblement, by transmission through our atmosphere, of the violet and blue sections of sunlight becomes obvious in the redness of the sinking sun. On the lower radiations telluric absorption acts more specifically. They are interrupted by a multitude of dark bands and lines

[1] The indications of this beautiful instrument, which depend upon the changes of electrical resistance in a strip of platinum, produced by differences of temperature, are believed to be reliable to one-hundred-millionth of a degree centigrade. Langley, *Phil. Mag.* July 1901, p. 123.

[2] *Proc. Royal Society*, vol. xlvi. p. 134.

[3] *Journal de Physique*, t. x. p. 16.

PLATE II.




Fraunhofer's A-Band in the Solar Spectrum. *Photographed by Frank McClean, F.R.S.*

certainly referable to it. The question as to the terrestrial or solar origin of such effects is evidently of fundamental importance to solar chemistry. It can be answered in two distinct ways. The earlier and simpler method is by comparing the spectra of the high and low sun. The groovings that gain strength with approach to the horizon stand self-declared as atmospheric, while lines unaffected by altitude tell plainly of exotic conditions. The latter class are much the more numerous. Of 3200 lines mapped by Thollon, 2090 are purely solar, 866 telluric, and 246 of compound production.[1] And the proportion is not very different in Dr. Becker's catalogue of 3637 spectral lines, published in 1890.[2] Among them 928 came out blackened in "low-sun" observations, and proved in the main due to the selective absorption of water-vapour. A considerable proportion, indeed, belonged to the "rain-band," and varied hygroscopically. Dry-air absorption is almost exclusively an oxygen product. It takes effect chiefly in three wide bands, Fraunhofer's "A" and "B" and Ångström's "*a*," all relieved against a crimson background. They are characteristic of cool oxygen. The molecules, whose vibrations they in a manner reflect, are broken up at high temperatures. They survive, however, the liquefaction of the gas at − 181° C. Professors Liveing and Dewar observed the atmospheric A and B in light that had been transmitted through three inches of this frigid fluid.[3] The rhythmical flutings composing the former are shown in Plate II., from a photograph by Mr. McClean. The work, of which it is a specimen, portrays the solar spectrum in seven sections, from D to below A ($\lambda$ 5800 to $\lambda$ 7700), the dispersion having been effected by means of a Rutherfurd grating of 17,296 lines to the inch.

Fig. 1 gives a general view of the atmospheric spectrum, so far as it can be seen, but it is largely invisible. Langley found the immense tract of the heat spectrum, down to wave-lengths of nearly six "microns,"[4] thronged with "cold" rays,

[1] Cortie, *Astronomy and Astrophysics*, vol. xi. p. 399.
[2] *Trans. Royal Society of Edinburgh*, vol. xxxvi. part i.
[3] *Phil. Mag.* August 1892.
[4] A micron = one-thousandth of a millimetre.

652 of which[1] were accurately determined from "bolographs," but remain, with few exceptions, chemically unidentified.

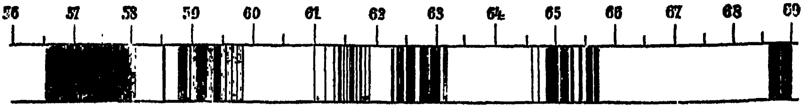



Fig. 1.—General View of Atmospheric Spectrum (Scheiner's *Astronomical Spectroscopy*, translated by Frost).

Fig. 2 reproduces Langley's drawing of part of the infra-red spectrum. The blank strip to the left shows the comparative brevity of the visible part of the scroll. The invisible part includes the distinctive signature of one other atmospheric constituent besides oxygen and water-vapour. Two strong bands in the infra-red are assigned by Knut Ångström to the absorption of carbon dioxide,[2] a substance of which four

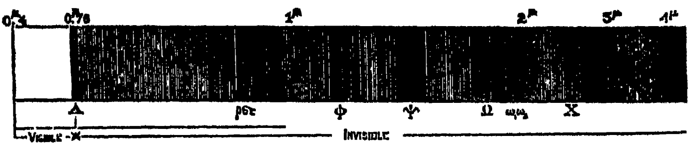



Fig. 2.—The Infra-Red Spectrum (Langley).

volumes are present in ten thousand of air at sea-level. The huge nitrogen envelope of our globe, together with its argon-ingredient, appears to be perfectly transparent to rays of all refrangibilities. The unexplained fact of its spectral nullity emphasises the inadmissibility of negative conclusions regarding the chemistry of the heavenly bodies.

The second peculiarity which distinguishes telluric lines is a negative one. They do not shift as the sun rotates. But lines genuinely emanating from the equatorial edges of the sun are displaced towards the blue by the advancing movement of the left or eastern limb, towards the red by the recession of the western limb. The juxtaposition, accordingly, of spectra from these two opposite sources serves as an unfailing test of the origin of their constituent markings, those claimed by the sun being perceptibly notched at the points of junction, while their telluric associates run on continuously.

[1] *Annals of the Smithsonian Astrophysical Observatory*, vol. i. p. 170.
[2] *Trans. Swedish Acad. of Sciences*, 1889; *Journ. de Physique*, t. x. p. 141.

Little has been added to knowledge of the sun's constitution by researches in the infra-red part of the spectrum. They are as yet crippled by the lack of metallic comparison-lines. Sir William Abney obtained in 1879 a modification of bromide of silver sensitive to slow heat-vibrations, and thus succeeded in directly photographing the solar spectrum between the wave-lengths λ 7600 and λ 10,750. Of 590 absorption-lines measured by him in this region in 1886,[1] only an insignificant fraction have been identified. All these belong to metals with low melting-points.[2] Further, certain bands which Becquerel succeeded in rendering visible by phosphorescence proved assignable to magnesium, calcium, sodium, and potassium.[3] This confirmation of the presence in the sun of potassium was far from superfluous, as only one line due to it can ordinarily be seen.

The recent era in solar chemistry may be said to date from Rowland's production of a perfect screw in 1882. This minor feat of ingenuity opened the way for vital improvements. Through its means, gratings ruled with almost ideal regularity became widely available, and the difficulties impeding the diffractive mode of light-analysis were removed or diminished. Now observations are mutually comparable only when the *absolute* wave-lengths of the observed rays are known; and they are derivable immediately from the diffraction spectrum, while in the refraction spectrum several complicating circumstances come into play. Hence the supreme value of gratings. For in the spectra afforded by them the positions of rays depend simply and solely upon the distance from crest to crest of the minute ethereal undulations they represent.

Rowland's photographic map of the solar spectrum[4] was a document in advance of the time. The amount of detail shown in it may be exemplified by the statement that 150 lines of absorption could be separately reckoned between H and K, the great calcium pair in the violet. No comparable delineations of terrestrial spectra (apart from that of iron)

[1] *Phil. Trans.* vol. clxxvii. p. 457. [2] *Ibid.* p. 462.

[3] Wiedemann's *Annalen*, Bd. xlvii. p. 208 (1892). See also E. P. Lewis's important investigations of "The Wave-Lengths of Infra-Red Lines," *Astr. Ph. Journal*, vol. ii. p. 1.

[4] Published in its enlarged form in 1889.

were, however, then extant; coincidences between the rays in them and Fraunhofer lines might, accordingly, be often apparent only, and devoid of chemical significance. Dr. Scheiner gave expression to a general sense of discouragement when he wrote in 1890: "It is unfortunately the case that less is known to-day as to the meaning of the Fraunhofer lines than was supposed to be known ten years ago." [1]

The need for fresh efforts was, however, promptly met. Photographic investigations of metallic spectra, fully coming up to the new standard of accuracy, were set on foot, among others, by Kayser and Runge at Hanover, by Hasselberg at Stockholm, above all, by Rowland and his coadjutors at the Johns Hopkins University. Here the spectra of nearly all the chemical elements have been photographed with high dispersion for the purpose of solar comparisons. And the end of the process is well within view. Measurements have already been carried far enough to give a multitude of identifications. Between 1895 and 1897 Professor Rowland published in the *Astrophysical Journal* a "Preliminary Table of Solar Wave-Lengths," extending from $\lambda$ 7331 to $\lambda$ 2976—that is, from dusky crimson up to the highest ultra-violet ray capable of penetrating the aerial barrier. He unhappily did not live to make the list definitive; but it comprises, as he left it, nearly 20,000 lines, about a third of which, by a rough estimate, may be confidently referred to absorption by various terrestrial substances. These are enumerated below, according to the number of lines associated with them in the sun. The corresponding atomic weights are given in a second column.

ROWLAND'S TABLE OF SOLAR ELEMENTS.

| Element. | Atomic Weight. |
|---|---|
| Iron (about 2750 line-coincidences) | 56 |
| Nickel | 58 |
| Titanium | 48 |
| Manganese | 55 |
| Chromium | 52 |
| Cobalt | 59 |
| Carbon (about 240) | 12 |
| Vanadium | 51 |
| Zirconium | 65 |

[1] *Die Spectralanalyse der Gestirne*, p. 177.

| Element. | Atomic Weight. |
|---|---|
| Cerium | 140 |
| Calcium (over 75) | 40 |
| Scandium | 44 |
| Neodymium | 140 |
| Lanthanum | 139 |
| Yttrium | 89 |
| Niobium | 94 |
| Molybdenum | 96 |
| Palladium | 106 |
| Magnesium (about 24 coincident lines) | 24 |
| Sodium (13) | 23 |
| Silicon | 32 |
| Hydrogen | 1 |
| Strontium | 87 |
| Barium | 137 |
| Aluminium | 27 |
| Cadmium | 112 |
| Rhodium | 103 |
| Erbium | 166 |
| Zinc | 65 |
| Copper (2) | 63 |
| Silver (2) | 108 |
| Glucinum (2) | 9 |
| Germanium | 72 |
| Tin | 117 |
| Lead (1) | 207 |
| Potassium (1) | 39 |

Of the following substances no traces could be found in the solar spectrum:—

| Element. | Atomic Weight. |
|---|---|
| Antimony | 120 |
| Arsenic | 75 |
| Bismuth | 208 |
| Boron | 11 |
| Cæsium | 133 |
| Gold | 197 |
| Indium | 113 |
| Lithium | 7 |
| Mercury | 200 |
| Nitrogen (vacuum tube) | 14 |
| Phosphorus | 31 |
| Praseodymium | 144 |
| Rubidium | 85 |
| Selenium | 79 |
| Sulphur | 32 |
| Thallium | 232 |

Argon may now be included among the non-apparent elements, and the presence in the sun of platinum and the metals cognate with it is still an open question. A metal belonging to a very different class was added to the number of solar ingredients by Messrs. Hartley and Ramage in 1897.[1] They convincingly identified two blue rays of gallium with Fraunhofer lines, pointing out that the proportion to iron of the new metal indicated as existing in the reversing stratum was by weight only one to thirty thousand. This accords well with its terrestrial relations. Gallium, discovered by Boisbaudrin in 1875, seems to be widely, but very minutely, diffused throughout the earth's crust. It occurs also in meteorites. It has an atomic weight of 70, is singularly volatile, and melts almost as readily as butter.

No substance has been more eagerly looked for in the sun than oxygen. But the search was long in vain. Henry Draper's recognition, in 1877, of *bright* lines of oxygen in the solar spectrum created a sensation, but proved illusory. J. C. Draper's *dark* lines were a still less plausible personation. Eisig ascertained in 1894 that none of the eighty-one emission-lines measured by himself occur in the solar spectrum.[2] Janssen demonstrated, by observations from the summit of Mont Blanc, that the *cool* oxygen-absorption conspicuous in it is of purely telluric origin;[3] and his conclusion was ratified by Dunér's application of the motion-displacement test.[4] Oxygen, however, is a substance of most complex, and perhaps unstable molecular structure. No less than six distinct spectra characterise it, two of them produced at low temperatures, and known through their absorptive effects alone; four derived from vacuum tubes, under varying degrees of electrical excitement. Moreover, one of these forms of emission is a series spectrum of the most intricate kind, comprising six different sets of harmonic vibrations, three made up of triple, three of single lines.[5] And here at last a significant coincidence was found. A triplet in the red part of the Fraunhofer spectrum, photographed by Higgs and McClean, was in 1897 clearly

[1] *Astrophysical Journal*, vol. ix. p. 214.

[2] *Astr. and Astrophysics*, vol. xiii. p. 506. [3] *Comptes Rendus*, t. cxi. p. 431.

[4] *Astr. and Astrophysics*, vol. xiii. p. 216.

[5] Runge and Paschen, *Wiedemann's Annalen*, Bd. lxi. p. 641 (1897).

identified by Runge and Paschen as a fundamental oxygen group[1] (see Fig. 3). The representation of the element, although certain and authentic, is reduced to a minimum.

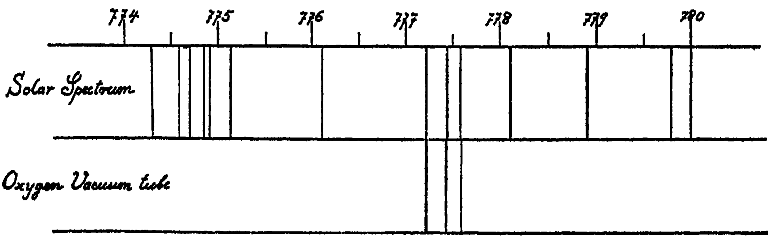



FIG. 3.—Oxygen-Triplet in the Solar Spectrum (*Astroph. Journ.* vol. iv. p. 318).

The spectrum of helium, which is analogous to the "series spectrum" of oxygen, makes no show in analysed sunlight, but appears bright above the limb. In the case of this substance, moreover, the usual order of detection was reversed. Its recognition as a chromospheric material preceded by nearly a quarter of a century the expulsion in Professor Ramsay's laboratory of an identical gas from clevite. But about helium more will be said presently.

So far, then, thirty-nine of the chemical elements are known to be common to the earth and sun, and the remaining forty may very well be so likewise. The absence from among the solar ingredients of any single terrestrial species of matter is unproved, and perhaps unprovable. The Fraunhofer spectrum sums up the combined absorption of a heterogeneous mixture of vapours. But the aggregate is widely different from what would be obtained by simply adding together the separate effects. For it is the outcome, so to speak, of struggle and survival. In a medley of ignited substances, the rays of certain among them predominate, while those of others are effaced. Thus non-metals, as a rule, make a poor figure in the spectral competition with metals, and this is doubtless one reason for their inconspicuousness in the sun. Apart from hydrogen, the properties of which are exceptional, only three metalloids, silicon, carbon, and oxygen, contribute to produce the Fraunhofer lines, and their contributions are feeble and

[1] *Astroph. Journ.* vol. iv. p. 317, vol. vi. p. 426. A second triplet is also possibly present, but it is less obvious than the first.

fragmentary. That other similar substances—selenium, sulphur, nitrogen, argon, and the rest—may be there, yet exercise no perceptible absorption, is amply possible.

The metals themselves, too, differ widely as regards conditions of visibility. Some are rich in strong lines, favourably situated for observation. Iron is an example. It emits thousands of rays, widely distributed over the spectrum, although most crowded in its higher sections; and they hold their own vigorously against the adverse influences of dilution. Again, the rare metal cerium is extraordinarily prolific of blue rays. No less than 400 were measured by O. Lohse in 1897 in the comparatively narrow region between λ 4000 and λ 4600.[1] Most of them, however, are quite feeble, and only twenty-nine have yet been identified as Fraunhofer lines. Those of bismuth, on the other hand, being all compound, are too diffuse (as Rowland observes) to be detected in sunlight. And most of the radiations of lithium are so highly refrangible as to fall under the ban of atmospheric exclusion. Their reversal in the solar spectrum can thus only be a matter of inference. That the inference should be negative is suggested by the absence of a strongly characteristic line in the carmine red. It *ought* to be readily seen, if lithium be a solar constituent. Its visibility should be promoted by the small atomic weight—only seven times that of hydrogen—and low fusing-point of the metal; and the persistence of the carmine beam is actually shown by its emergence in the spectrum of the Bessemer flame. Yet it is unlikely that lithium is, in fact, missing from the sun. The case deserves particular attention.

Heavy substances are obviously at a disadvantage as regards the production of absorptive effects. Their vapours must tend to lie low, like carbonic acid in the earth's atmosphere. Hence the average lightness of the solar elements is only what we should expect. The mean atomic weight of the thirty-five metals represented in the Fraunhofer spectrum is, in fact, just 72, while that of the non-apparent metals is 159. Atomic weight, however, is only one of many conditions affecting this result. The inclusion of lead-absorption in the scroll, and the exclusion from it of lithium, sufficiently prove that vapour-density is far from being alone concerned.

[1] *Astroph. Journ.* vol. vi. p. 101.

The detection of carbon in the sun was difficult and noteworthy. Originating with Sir Norman Lockyer in 1878,[1] it was ratified by Trowbridge and Hutchins in 1887,[2] and still more decisively ten years later by Rowland. It was, and could only have been made, photographically. The visible carbon bands are barely discernible in the Fraunhofer spectrum. One, however, in the ultra-violet (beginning at λ 3883) comes out unmistakably on sensitive plates. It is due, according to the best authorities,[3] not to elementary carbon, but to cyanogen—that is, to carbon in its combination with nitrogen. The fact is not easy to explain. No other compound body is known to exist in the sun; and it might have been judged *à priori* impossible that any could prove capable of resisting the enormous temperature reigning near the photosphere. Sir Norman Lockyer attempted to get rid of the anomaly by locating the absorbing cyanogen in coronal regions, where relative coolness must prevail; but recent observations point rather to its presence as a shallow, deep-lying stratum. It is certain, moreover, that the line-spectrum derived from free carbon through the exciting influence of a powerful electric spark has no counterpart in the sun. We are then bound to admit, at least provisionally, that the ultra-violet solar band genuinely indicates absorption by cyanogen. There is a further complication. The green fluting, a few *shreds* of which were measured by Rowland among the Fraunhofer lines, makes part of the typical hydro-carbon spectrum given primarily by acetylene. The whole subject is indeed thick-set with embarrassing considerations; they need careful sifting out. Carbon molecules are remarkably sensitive in their modes of vibration, four of which have been separately distinguished.[4] The conditions, however, prescribing the replacement of one by another are still in large measure obscure. Temperature is concerned, but it is not alone concerned; density, admixture with foreign substances, perhaps variations of electrical state, come into play. Yet the

[1] *Proceedings Royal Society*, vol. xxvii. p. 308.

[2] *American Journ. of Science*, vol. xxxiv. p. 348.

[3] Kayser and Runge, *Wied. Annalen*, Bd. xxxviii. p. 80; Crow and Basquin, *Astroph. Journ.* vol. ii. p. 103.

[4] Hartley, *Proc. Royal Society*, vol. lv. p. 348.

broad certainty has been gained that carbon, in one, if not in several of its many forms, exists in the photospheric neighbourhood. And this has an important bearing, not only upon theories of the solar constitution, but also upon questions of great interest regarding solar relationships with the stars.

Professor Rowland disbelieves in any fundamental difference between solar and terrestrial chemistry. The earth, heated to the solar pitch, would give, he affirms, a spectrum virtually identical with that of the sun. Yet we cannot well ignore evidences, apparently valid, of some real diversity. Even if all our "elements," without exception, are found in the sun, they are unlikely to occur in the same proportions there as here; *quantitative*, if not *qualitative* dissimilarity must be recognised. Thus certain metals, so scarce that their ores rank as mineralogical curiosities, produce marked effects of absorption in the sun. Zirconium, yttrium, cerium, lanthanum may be instanced. Titanium and vanadium are multitudinously represented in the solar spectrum. Hasselberg ascertained for the former substance in 1896 no less than 562 coincidences with Fraunhofer lines out of a total of 718 photographed by him from the metal.[1] On the exclusion of the feeblest rays on his plates as being of quite uncertain origin, the percentage of agreement rose to 88 per cent. The Swedish spectroscopist might well claim that "the presence of titanium in the solar atmosphere is confirmed, with even superfluous evidence, by these investigations."

Vanadium—first registered as a solar constituent by Sir Norman Lockyer—might be called the satellite of titanium. Where one is, the other is sure to be not far off. Hasselberg's recent discovery of vanadium in the Scandinavian mineral rutile[2]—a form of titanic acid—accentuates the relationship. Both occur, too, although very scantily, in lead and iron ores, and just traceably in trap and basalt. This close association may be accounted for by inherent resemblance. The atomic weight of titanium is 48, that of vanadium 51. Both are eminently infusible. They share the unusual peculiarity of exhibiting a strong high-temperature affinity for nitrogen.[3]

[1] *Astroph. Journ.* vol. iv. p. 232. [2] *Ibid.* vol. v. p. 194.
[3] Moissan, *Le Four Électrique*, pp. 257, 261.

They exemplify, moreover, a transition-stage from metals to metalloids, titanium approximating to silicon, vanadium to phosphorus. Both, it may be added, have been detected in meteorites. A large proportion of the numerous rays emitted by vanadium are reversed in the sun, but somewhat faintly reversed, except in cases of special disturbance, and with these we are not at present concerned. It is worth remarking that titanium and vanadium, notwithstanding their near kinship, physical and chemical, show no coincident spectral lines. In these twin elements, if in any, a common material substratum might be looked for. There is not the slightest sign, however, that it exists.

The new metal germanium is an obvious solar constituent; yet it only *lurks* in one uncommon terrestrial product. Winkler recognised it in the mineral argyrodite in 1886. And the sun appears to be much richer than the earth in Sir William Crookes's "meta-elements."[1] The number of these is almost indefinite; their individualisation, resting upon the dubious principle, "one band, one element," is often imperfect or misleading; and many of the evasive substances, ranked for a time as separate entities, have failed to make good their footing, and relapsed into the condition of "sub-aggregates of atoms." The chemistry of "rare earths" has of late assumed a kind of departmental importance. It began in 1794 with the extraction by the Finnish chemist Gadolin of "yttria" from a jet-black material picked up at Ytterby, near Stockholm. "Ceria," detected in 1803 in the "heavy stone" from Bastnäs, was named after the first asteroid; "lanthana," obscurely associated with it, came to light in 1839; "didymia," "terbia," "erbia," successively followed.[2] The opening, in 1878, of a fresh and fairly abundant source of supply in the American mineral samarskite started vigorous inquiries into the nature of these remarkable bodies; and Cleve enumerated in 1895 nine fully characterised metallic bases, most of them emitting, under electrical excitation, a brilliant array of spectral beams. The nine "rare" metals are scandium, yttrium, lanthanum, cerium, erbium, praseodymium, samarium, gadolinium, and ytterbium. The first four absorb strongly

[1] *Journal Chemical Society*, 1887, vol. lv. p. 284.

[2] Cleve, *Trans. Chem. Society*, 1895, p. 470.

in the sun, where the presence of erbium and of neodymium, a constituent of the original didymium, is also evident. Twenty-two additional meta-elements swell Sir William Crookes's "suspense account," but only a minority are at all likely to obtain ultimate recognition as substantive forms of matter. Perhaps the surest test of their quality will be found in the appearance among the Fraunhofer lines of their characteristic emissions. Those, at any rate, of terbium, holmium, and thulium should be carefully looked for.

The light of glowing metallic vapours tends, as we have seen, to suppress or efface the rays of non-metals. Professor Trowbridge made some experiments in 1896 with a view to determining the conditions of obliteration. Photographing on a single plate the spectra of pure carbon and of an electric arc between carbons containing 28 per cent of iron, he found that the iron ingredient sufficed very nearly to wipe out the carbon bands in the arc.[1] "This proportion, therefore, of iron," he remarked,[2] "in the atmosphere of the sun, were there no other vapours of metals present, would be sufficient to prevent our seeing the full spectrum of carbon." An interesting illustration was thus afforded of a fundamental principle in solar interpretations. The principle, indeed, has scarcely yet begun to be applied. Hitherto the absorptive effects of each of the forty substances vaporised above the photosphere have been considered apart. But they are not independently produced. They are often profoundly modified by extraneous action. A systematic investigation of the various modes in which it comes into play is desirable, although likely to prove arduous. "There is at the present time," Dr. Ames wrote in 1895,[3] "no more fruitful field open to research than that of the study of the influence of the presence of one substance upon the spectrum of another." And Mr. Percival Lewis's recent treatment of the subject has had the preliminary result of showing that "very small traces of an impurity in a gas may cause considerable changes in its spectrum, whether this impurity be chemically active or not."[4] The changes, too,

[1] *What is Electricity?* p. 299.
[2] *Amer. Journ. of Science*, vol. i. p. 331, 4th series.
[3] *Astroph. Journ.* vol. i. p. 89.
[4] *Ibid.* vol. x. p. 161.

are in many ways perplexing. They are governed by no traceable rules, depending apparently, in each case, upon intimate, and to us unknown, molecular relations with electricity.[1] The explanation of their anomalies is evidently needed for the satisfactory future progress of solar chemistry.

[1] R. A. Porter, *Astroph. Journ.* vol. xv. p. 281.

# CHAPTER III.

## PECULIARITIES OF THE SOLAR SPECTRUM.

THE solar spectrum is densely thronged with unidentified lines. Of these upwards of twelve thousand have been measured and registered, but lack chemical interpretation. They are, however, on the way to receive it. Their recognition will doubtless attend the gradual progress of acquaintance with metallic spectra. Thus cerium, scandium, and other bases of "rare earths" may satisfactorily account for a considerable proportion of them, these substances emitting crowds of rays, as yet only in part recorded. But besides, say, twelve thousand catalogued "unknown" lines, an inestimable number remain unnoticed.[1] They are still, as it were, "in the street"; they have not been admitted even to the antechamber of science; the preliminary steps to their identification have not been taken. They will of course be taken in due time, little by little, as the photography of the Fraunhofer spectrum is brought nearer to perfection; and to many of them chemical meanings full of interest will certainly be assigned. Nevertheless, it can scarcely be expected that the significance of all can ever be made plain. To the very end, probably, a residuum will keep the secret of an origin due to forms or conditions of matter strange to terrestrial experience.

That the *type* of the sun's spectrum becomes modified in the course of ages—that it has been, and will again be different from what it now is—may be admitted without hesitation. But this evolutionary change is effected imperceptibly at more than millennial leisure. It might, however, have been expected that transient alterations would manifest

[1] Fowler, *Knowledge*, vol. xxiii. p. 11.

themselves—alterations caused by tumultuous movements in the "reversing layer," or connected, possibly, with periodical outbreaks of spots and prominences. Yet almost none of this definite and obvious character have been noticed. Only a few lines may be set down as somewhat vaguely and indeterminately variable. To take a few examples. In 1891 Father Sidgreaves of Stonyhurst obtained several photographs of the group *b* (magnesium and iron) in the green part of the spectrum. They showed with excellent definition more faint lines than are contained in Rowland's or Thollon's maps; yet one relatively strong in them—"Winlock's No. 17"—was barely discernible.[1] This indication of change does not seem to have been followed up. Again, Sir Norman Lockyer noted in 1873 the disappearance of a zinc line in the red (Ångström $\lambda$ 6361·16), which, nevertheless, was seen as usual in 1878, and has not since been missed.[2] The most recent instance of the kind was vouched for from Baltimore. To a faint, slightly nebulous line of unknown origin in the ultra-violet ($\lambda$ 3719·796) Rowland attached the note, "Variable, though not atmospheric." Jewell[3] describes it as situated within the shading of a strong iron line, and as "quite distinct upon some plates, while not visible upon others showing lines closer to the iron line, and much weaker than the variable line," as it originally appeared. It has also been photographed in an intermediate condition, so that its fluctuations of intensity may be said to be ascertained, although their law and cause remain wholly obscure. The only hope of learning anything about these is by continuous and minute observation, which should extend to other suspicious cases of the same kind. Certain interesting questions might thus be answered. For instance, are the alleged alterations connected effects of some general disturbance, or do they occur sporadically, each on its own account? Can they, in any way, be brought into relation with the spot cycle? Are they visible in light taken indiscriminately from all parts of the sun, or are they confined to special localities? These may serve as specimens of the inquiries suggested by phenomena, perhaps none the less significant for being inconspicuous. With the camera at

[1] *Astr. and Astrophysics*, vol. xi. p. 79. [2] Cortie, *ibid.* p. 591.
[3] *Astroph. Journ.* vol. iii. p. 106.

hand the task of daily comparison becomes easy and simple. As Professor Hale wrote in 1896,[1] "Every photograph of the solar spectrum taken with high dispersion must now be regarded as a document of great value, which may ultimately reveal irregular or periodic changes in the condition of the gases and vapours of the solar atmosphere."

The Fraunhofer lines have of late forfeited their early reputation as "constants of nature." They are not really "fixed"; their positions in the spectrum are affected by several minutely modifying causes, and they cannot, accordingly, be depended upon as standards for the most refined measurements. It is true that only the extreme accuracy of modern methods has caused them to "step down" from the high level of invariability, for their deviations are very small, and might, superficially regarded, appear negligible. They are of two kinds, physical and kinematical, the former being produced in the very act of emission, the latter in the course of transmission. Pressure-displacements and motion-displacements are, in fact, respectively concerned.

Symptoms of a persistent shift of the Fraunhofer lines towards the red were first detected in 1890 by Professor Lewis E. Jewell of the Johns Hopkins University. Persistent, although unequal. It is not the same for the lines of different elements; it is not even the same for all the lines of the same element. Motion, then, is not its cause. Fortunately, a clue was supplied by laboratory-experiments. Attentive study of the behaviour of metallic lines under varying conditions showed that "with an increase in the amount of material in the arc there was increasing displacement towards the red." "Considering the subject carefully," Professor Jewell adds, "there seemed no reason to doubt that the wave-length of a line depended, to a certain extent, upon the conditions under which the material producing the line was present in the electric arc, the vacuum tube, or the solar atmosphere; or, in other words, the vibration period of an atom depends to some extent upon its environment. An increase of the density of the material, and presumably an increase of pressure, seemed to produce a damping effect upon the vibration period."[2] Confirmatory results were obtained

[1] *Astroph. Journ.* vol. iii. p. 157. [2] *Ibid.* pp. 92, 93.

by Messrs. Humphreys and Mohler,[1] and the assumption of a constant vibration-frequency as an essential attribute of the ultimate particles of matter had to be finally abandoned.

The observed changes are clearly distinguishable from ordinary temperature effects. Lines are often broadened; under peculiar circumstances they may be unsymmetrically broadened by thermal influences; but simple displacements are never due to heat. Moreover, they can be produced artificially by condensing the air about an electric arc, so that their immediate cause is not doubtful. "It was often easy," according to the Baltimore investigators, "to observe a line gradually change its position while the pressure was being let off without alteration in width or other appearance."

The general upshot of their inquiries[2] was to show that the spectral shifts in question, far from being an isolated phenomenon, stand in close relationship to all the most intimate properties of matter. Their amount, *cæteris paribus*, is proportional to the pressure and to the wave-lengths of the shifted lines. It differs, however, for each series in a given spectrum. For different substances it is usually large or small in the inverse ratio of the absolute temperatures of their melting-points. Again, it is largest for those substances which expand most readily with heat. Finally, and most significantly, line displacements are, in the same group of elements, proportional to the cube roots of their atomic weights. Or, as Mr. Humphreys expresses it, "The shift of similar lines is a periodic function of atomic weight, and consequently may be compared with any other property of the elements which itself is a periodic function of their atomic weights"—that is to say, the measured displacements show recurring maxima and minima in passing from one to the next of Mendeléef's elemental families. Their gradations thus correspond with those of other physical attributes of material species, and plainly imply that the retarded vibrations are executed by "ultimate" atoms. The confirmatory fact should be noted that band-spectra, universally associated with aggregates of atoms, display no sensitiveness to pressure.

[1] *Astroph. Journ.* vols. iii. p. 114, iv. p. 175, vi. p. 169.

[2] *Ibid.* vol. vi. p. 225.

And by pressure in this connection is to be understood, not the separate density of the vapour emitting the damped rays, but the total pressure of all the substances promiscuously diffused throughout the stratum or enclosure.

Its complex effects add, in some respects, to the difficulty of interpreting spectral appearances; but they lend to them, on the other hand, new and unlooked-for significance. In solar inquiries more particularly, they have started a fresh lead, sure to be followed up. Thus indications may be gathered from them as to the relative altitudes in the sun's atmosphere at which different Fraunhofer lines originate, no less than as to the absolute pressures to which they correspond. These are lower than might have been anticipated. They range, according to Professor Jewell, "from little more than zero to only two or three atmospheres, though the shading of the stronger lines may be produced at a greater pressure."[1] The subject, however, has not got beyond the stage of inception. One important branch of it, the discrimination of lines belonging to the same series, is barely sketched. The phenomena of displacement through pressure evidently involve much more than is yet apparent. They must be present in stars and nebulæ, and may afford curious disclosures regarding their states of density and rarity.

The Fraunhofer lines are, as a rule, narrow and sharp; but minute photographic study reveals, in a certain proportion of them, singular complexities of structure. These are illustrated from Professor Jewell's observations in Fig. 4, which shows graphically, by four typical examples, the comparative distribution of light in corresponding solar and arc lines.

No. i., a green ray of iron, is bordered in the sun (where it is of course reversed) by a filmy illumination, "the remains of an emission line, either produced at the photosphere, or lower down in the solar atmosphere than the absorption line."[2] The notch at the summit of the same line gives evidence of radiation at a high level. It is, in fact, an *abortive* bright iron line, superposed upon a strong absorption line, itself superposed upon a faint effusion of light of identical quality from underlying vapour. Thus this single line is built in three stages, although the foundation and coping are

[1] *Astroph. Journ.* vol. xi. p. 240. [2] *Ibid.* vol. iii. p. 100.

barely discernible as traces of luminosity. In Nos. ii. and iii., "shaded lines" are depicted in the same manner as the "sharp line" in No. i. They belong respectively to iron and magnesium ($\lambda$ 5183·8 $= b_1$). Their characteristic feature is the outlying obscurity, which deepens from the edges towards the central shaft. Professor Jewell remarks that the gas pro-

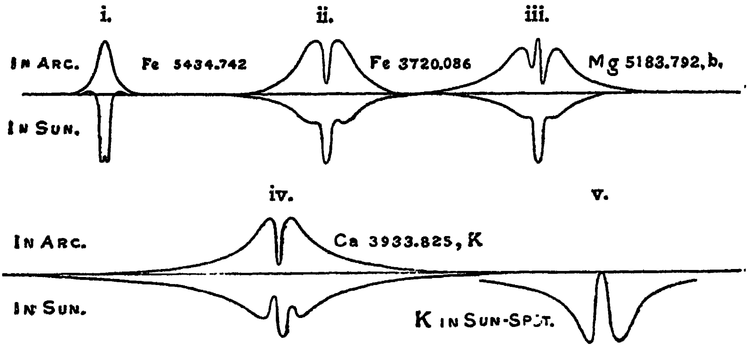



FIG. 4.—Curves representing the Distribution of Light in Fraunhofer and Arc Lines (*Astroph. Journ.* vol. iii. p. 100).

ducing these shadings "extends through a much greater range of pressure" than that giving rise to the green iron line (No. i.), while the clean-cut line in the middle must be due to absorption "much higher up in the solar atmosphere, where the pressure is very much less." Similar appearances are conspicuous in the great calcium pair H and K (see Fig. 4, No. iv.). Here the abnormal breadth of their wing-like appendages proves that the "absorption must persist through an extreme range of pressure, or that the amount of calcium gas varies enormously in the solar atmosphere where this absorption is produced." These lines are obviously twice reversed. A stratum of radiative calcium is apparently interposed, in the sun's neighbourhood, between two absorptive strata of the same material. That their arrangement is, however, subject to some kind of disturbance is indicated by the irregularity of the diagram; nor is it always disturbed to the same extent. "Upon some plates," Professor Jewell says, "the central absorption line is almost symmetrical with respect to the emission line, while upon other plates its unsymmetrical character is very marked, the central line being displaced

considerably towards the red, and the part of the emission line on the violet side of the central line being much the strongest." Motion-displacements due to ascending and descending currents are thought to be in question,[1] but there are obstacles to be removed before this explanation can be unreservedly accepted. The extreme difference of velocity suggested by the observed dissymmetry of the calcium lines amounts to no more than 75 miles a minute, but is notably variable. All the "shaded lines" in the spectrum appear to be similarly affected, though in a minor degree. Thus the descending motion corresponding to the narrow central components of the sodium "D" are at the rate of barely one-fifth of a mile per second. Most of the fainter lines, on the contrary, indicate ascending currents over the solar surface at an average speed of about a third of a mile a second.[2] Motion-displacements, besides, due to the earth's rotation and the eccentricity of its orbit, can be detected, and have been allowed for. These latter minute corrections naturally apply to all the solar lines without distinction.

Enough has been said to give an idea of the manifold considerations which have to be taken into account in estimating the *true* wave-lengths of the solar absorption rays. They are changed, according to a special and complex law, by the sun's rotation; they are changed by the movements of approach or recession of the earth as a whole, as well as of each particular spot on the earth; they undergo alteration through the solar atmospheric circulation; they are affected by pressure, perhaps by other undetected influences, and each of these modifying causes acts variably, either in time, or according to locality on the solar surface. Happily, most of them act only to an infinitesimal extent; but their unquestionable, although slight effectiveness illustrates very strikingly the subtlety which every increase in accuracy necessitates in the methods of science.

An embarrassing peculiarity of the Fraunhofer lines is their virtually uniform intensity all over the sun's disc. Just as the telluric bands develop with the sinking of the sun, they ought to become strengthened near the limb; yet

[1] *Astroph. Journ.* vol. iii. pp. 102, 103 (Jewell), p. 158 (Hale).
[2] Jewell, *Astroph. Journ.* vol. xi. p. 236.

they remain sensibly the same, notwithstanding the greatly augmented depth of the absorbing strata traversed by the light before reaching the eye. This is really a glaring anomaly, and one almost forgotten through sheer hopelessness of getting rid of it.

In concluding this brief chapter we would once more draw attention to the curious individualities of the Fraunhofer lines. They are constructed, in many cases, at successive levels; they are modified by various influences. Some are of hair-like fineness; others, emanating from an identical substance, have nebulous edges. Moreover, the sharp and the diffuse lines respond differently to pressure, so that their characteristic aspects are significant of profound distinctions in their mode of origin. The more closely, in fact, these mysterious rulings are examined, the less trivial or casual their slightest diversities appear. They are charged with meaning, transcending, in part, our actual powers of interpretation, but challenging efforts towards that end, which cannot fail to breach, if they do not wholly raze, the ramparts of ignorance.

# CHAPTER IV.

## THE REVERSING LAYER.

During the eclipse of 22nd December 1870 a new phenomenon came into view. Professor Young of Princeton, New Jersey, was the fortunate observer. With the slit of his spectroscope tangential to the sun's limb and perpendicular to the moon's advance, he awaited the moment of second contact. The thin solar crescent narrowed second by second; at last it vanished; then "all at once, as suddenly as a bursting rocket shoots out its stars," the ordinary Fraunhofer spectrum previously visible was replaced by a serried array of bright lines on a dark background. They seemed a complete reversal of the familiar absorption-rays, and the impression was also conveyed to Mr. Pye, a member of the same party, of "all the dark lines being converted into bright ones."[1] The "flash" at the edge of the eclipsed sun was not unlooked for. Something of the kind had been anticipated as the due accompaniment of the beginning and end of totality. For Kirchhoff's explanation of the Fraunhofer lines implied the interposition, between the eye and the sun, of a screen of glowing vapours, which should be separately, if only instantaneously, visible on the withdrawal of daylight glare—visible, that is to say, spectroscopically; with the telescope nothing more distinctive than a silvery shimmer[2] corresponds to the dazzling variotinted fireworks disclosed by the prism.

But their disclosure was not enough; they demanded close investigation. The question is fundamental in solar physical theory whether the flash is the true reversal of the

[1] *Memoirs Royal Astr. Society*, vol. xli. pp. 339, 434 (Ranyard).

[2] *Ibid.* p. 115.

Fraunhofer spectrum, and no conclusive answer could be given to it except by photographic means, visual reports as to the details of so intricate and evanescent an apparition counting for very little. Twenty-six years, however, elapsed before a permanent record of it was secured. The result ensued from a skilfully-timed snapshot by Mr. Shackleton at Novaya Zemlya during the Arctic eclipse of 9th August 1896. He gave an exposure of half a second with a "prismatic camera"—a simple form of spectrograph, destitute both of slit and collimating lens, the employment of which in eclipse work has been vigorously promoted by Sir Norman Lockyer. An impression was thus caught of singular interest and value. We may quote Professor Young's description of it. "The photograph," he writes,[1] "shows a long range of several hundred bright curved images, of which there are nearly 250 in the blue portion of the spectrum between F and H. About 25 are much more extensive and conspicuous than the others, and are images of the chromosphere and prominences. They are due to hydrogen, calcium, helium, strontium, and one or two other elements which often appear in the chromosphere. The rest are simply reversals of the Fraunhofer lines, as Mr. Shackleton has shown by developing the flash spectrum into a bright-line spectrum of the usual form (which is easily done by a simple mechanical contrivance), and comparing it with an ordinary dark-line solar spectrum photographed with the same camera and prisms, but with the addition of a collimator and slit. The agreement is practically complete, although there are two or three somewhat conspicuous Fraunhofer lines which are missing in the flash spectrum, probably because they originate, not above the surface of the photosphere, but in its depths, as probably also do the wide, hazy shadings that accompany the H and K lines and some others; but this is a matter for further investigation."

The solitary success of 1896 was manifolded a year and a half later. "Reversing-layer" photography stood in the forefront of the programme of work for the Indian eclipse of 22nd January 1898, and the documents collected during its hundred seconds of obscurity showed that a complete mastery

[1] *The Sun*, ed. 1897, p. 358.

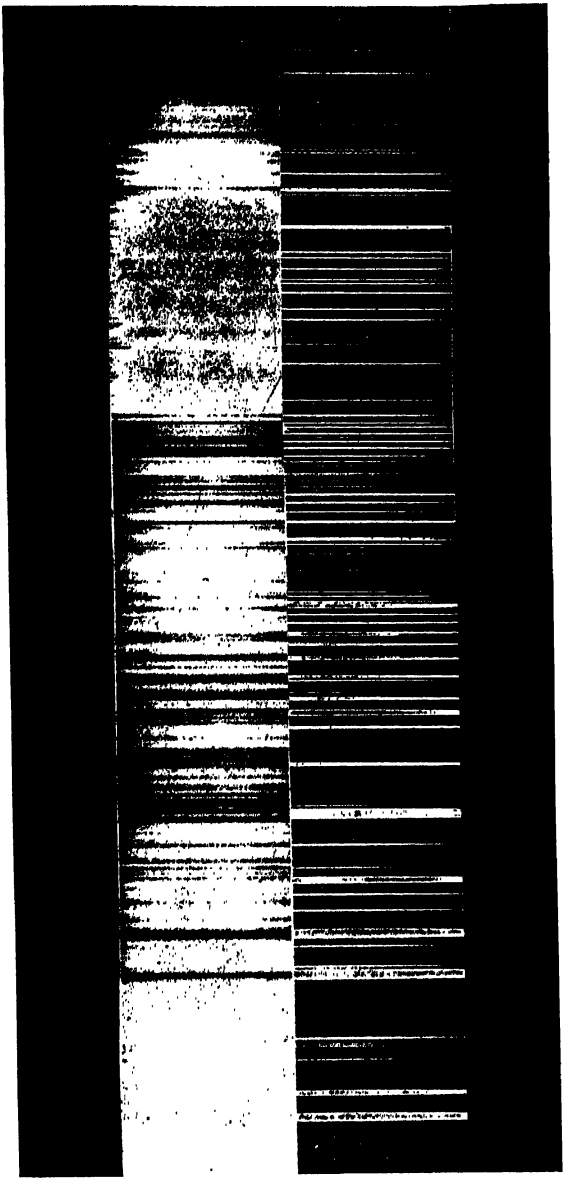
of the art had been attained. Sir Norman Lockyer and Mr. Fowler, Captain Hills, Mr. Evershed, and Professor Naegamvala secured photographs of the flash, not only in its full development, but also when incipient and vanishing, so that the phenomenon could be traced at leisure throughout its brief phases. Two specimens are reproduced in Plate III., both taken instantaneously by Mr. Evershed with a prismatic camera of $2\frac{1}{4}$ inches aperture and 36 inches focus.

The conventional straight appearance of the lines results from the employment of a cylindrical lens to give breadth to narrow slices of the curvilinear originals. The upper section represents the spectrum of the last thread of sunlight just as the accustomed dark lines were fading out before the incoming of their bright correlatives. The range is from below H and K—the strong pair to the left—to $\lambda$ 3350 in the ultra-violet.[1] The lower section corresponds to a moment twenty seconds later, when the continuous light was gone, and vivid rays dominated the field. Amid the throng, twenty-seven members of the hydrogen series are recognisable, and three titanium lines rival them in importance.

Ample materials were provided during the eclipses of 1898, 1900, and 1901 for at least a preliminary discussion as to the true character of the reversing layer, although the difficulties still remaining to be encountered are neither few nor trivial.

To begin with, the fact has been ascertained that a shell of mixed incandescent vapours, five or six hundred miles thick, encloses the photosphere on every side. We see it, however, in projection. The line of sight penetrates it tangentially at the edge of the sun, and to an extreme depth near the base of about forty thousand miles. Between the reversing layer and the chromosphere there is no solution of continuity; to some extent, undoubtedly, the lower merges into the upper formation; yet they are essentially distinct. Each has its own spectrum apart, notwithstanding a certain amount of community, apparent, casual, or partial. Thus since the reversing layer is visually accessible only through the enveloping chromosphere, the spectrographic prints taken at sun-and-moon contacts are inevitably composite. They include the chromospheric

[1] Only the more refrangible parts of the portrayed spectra have been reproduced. The complete images reach down to $\lambda$ 6000 in the orange.



Flash and Cusp Spectra compared. Ultra-Violet Region λ 4100 to λ 3350.

together with the "flash" rays. Discrimination is, however, facilitated by the notably greater length of the arcs representative of the former corresponding with the higher extension of the substances emitting them. The class of discrepancies between the flash and the Fraunhofer spectrum thus accounted for are discrepancies by excess. The flash includes helium rays; the Fraunhofer spectrum has none. The flash exhibits the complete hydrogen series up to its extreme limit in the ultra-violet; the Fraunhofer spectrum reverses only its visible members. Titanium lines strong in the flash are feeble in the Fraunhofer spectrum; besides other analogous dissimilarities. Yet they do not affect the claim of the reversing layer to be, speaking broadly, the locus of solar absorption. Rather they bring us face to face with the totally different question, Why do the chromospheric gases exercise no appreciable arresting effect upon the light transmitted through them? Later on we shall attempt to answer it; here we need only remark that the rays from the chromosphere cannot be excluded from photographs of the flash. They necessarily appear in them, and it was known beforehand that they had no counterparts in the Fraunhofer spectrum.

There are besides discrepancies by defect. Many solar absorption lines do not show bright at the first and last instants of totality. But this is easily understood. Some are doubtless too faint to assert their presence photographically. Others may be supposed, with the utmost probability, to originate out of sight at the base of the reversing stratum. The shadings of H and K certainly do, for the central lines start out clear, though strong, in the flash, and their hazy appendages are indubitable products of augmented pressure. Nor do the denser vapours rise high enough to make any perceptible display. Mr. Evershed tells us [1] that, while nearly all the metals with atomic weights less than 60 are represented in the sun's marginal spectrum, none, of which the ultimate particles are heavier than 92, make any assured contributions to it. A formation at least five hundred miles in vertical extent must vary widely between top and bottom both in composition and density. So at least we should reasonably anticipate. In point of fact the changes indicated are surprisingly slight.

[1] *Phil. Trans.* vol. cxcvii. A. p. 402.

One criterion is available by which chemical differences can be correlated with differences of depth. This consists in the various lengths of the curved lines representing the emissions of the sundry constituents of the "layer."[1] Substances attaining high altitudes, like the chromospheric gases, give long arcs because their visibility extends over a wide section of the sun's circumference, while low-lying materials, illuminating a narrow verge, are characterised by short arcs. They are, moreover, the most difficult to catch as the moon goes by. Now the great majority of the flash lines are of a nearly equal length, corresponding to an arc of about 40° on the solar limb, and this equality implies a considerable approach to uniformity of constitution throughout the greater part of the momentarily exposed layer. But its basal stratum, perhaps not more than a few miles in thickness, should be that most effective in absorption,[2] and it forms a crescent much too fine to be directly seen. Here below, then, down near the photosphere, missing Fraunhofer lines with no apparent corresponding radiations may be produced; nay, *must*, since there is absolutely no evidence of the corresponding light-stoppage taking place in, or above the chromosphere.[3] Mr. Evershed's conclusion is indeed fully warranted, that "the flash spectrum as a whole appears to represent the upper more extensively diffused portion of a stratum of gas, which, by its absorption, gives the Fraunhofer spectrum."[4] The appellation "reversing layer" would then seem to be no misnomer, but to indicate correctly the seat of the linear absorption which serves as our alphabet for spelling out the secrets of solar chemistry.

The density of this vaporous envelope is measurable by the "pressure shifts" of the Fraunhofer lines. It would seem to be nowhere *less* than that of our atmosphere at sea-level; otherwise displacements towards the *blue* end should occur, and none such are perceptible. Nor, on the other hand, is there proof of its exceeding, even in the lowest depths, three or four times the standard value. So that the increase of pressure downward is exceedingly slow—a fact to be carefully

[1] S. A. Mitchell, *Astroph. Journ.* vol. xv. p. 118.
[2] *Monthly Notices*, vol. lviii. p. 300 (Evershed).
[3] Hale, *Astroph. Journ.* vol. iii. p. 160.
[4] *Proc. Royal Society*, 17th Jan. 1901.

noted. The distinction (already adverted to) between the effects of total and of partial pressure is also most important. Through the former the positions of spectral rays are modified, through the latter their characters. In other words, the shifts of the Fraunhofer lines correspond to the sum of incumbent vapours, while the quantity of each separately present determines their width and diffuseness. Most are associated, by their fineness and sharpness, with *individually* tenuous substances. The hydrogen lines, for instance, represent, according to Mr. Maunder,[1] a pressure of only one-hundredth of an atmosphere. But the indications in this respect, as in others, vary greatly for the different vapours.

The most refractory substances, such as titanium and vanadium, are volatilised in the reversing layer. It is, then, enormously heated. But it is cooler than the photosphere, since its rays show dark against the vivid background they are projected upon. Now the temperature of the photosphere, by the most authentic recent determination, is about 6600° centigrade,[2] and this marks an upper limit for the temperature of the reversing layer. A lower limit is fixed by the temperature of the electric arc, estimated at 3500°. The much higher grade of the spark is almost certainly not attained. The inverse behaviour of two magnesium lines, first commented upon by Professors Liveing and Dewar,[3] led Dr. Scheiner to this conclusion.[4] One at $\lambda$ 4352 is prominent in the sun and strong in the arc, but fades out in the spark; the other, at $\lambda$ 4482, of which a mere trace is perceptible in the sun, is a characteristic spark-product. It must, however, be borne in mind that comparative temperatures are subject to great uncertainty where electricity is the exciting agent. Dissentients are even to be found from the broad proposition that the spark is hotter than the arc; nor is it one capable of direct demonstration. Qualifying circumstances come in, and their separate effects are not easily unravelled.

M. Deslandres made some curious experiments at Paris in 1894 in photographing the sun by means of the dusky rays

[1] *Knowledge*, vol. ix. p. 50.
[2] W. E. Wilson, *Proc. Royal Soc.* 12th Dec. 1901.
[3] *Ibid.* vol. xxx. p. 93.
[4] *Sitzungsberichte Berlin Akad. der Wiss.* March 1894.

in its spectrum.[1] For their isolation he used a "double slit"; and since they are only comparatively dark, no difficulty was encountered through want of actinic power in the rays dealt with. He thus succeeded in obtaining with each a monochromatic picture of the sun delineated exclusively with emissions from some particular ingredient of the reversing layer. The uniformity of elemental distribution was, by this ingenious device, put to the test. Photographs of the disc, for instance, taken *on* an iron line might be expected to show different features from those taken on calcium or magnesium lines if local accumulations of those vapours were present; but no divergences of the kind became perceptible. The composition of the absorbing envelope did not seem to vary *regionally.* The investigation, however, was not carried far, and would be worth prosecuting.

The *fact* of the existence of a true reversing layer may now be looked upon as established; yet the *mode* of its existence remains in several ways perplexing. The slightness of its absorptive action needs explanation at the outset. One notes with amazement that the miniature atmosphere surrounding an electric arc is equally effective for light-stoppage with this ocean of vapours. Then there is the singular, and perhaps related circumstance that the spectrum from the limb is not more deeply grooved than the spectrum from the central parts of the disc. The results upon light of being sifted through six hundred and through twenty thousand miles of the mixed materials glowing near the sun are virtually the same. Their comparative tranquillity, too, is unexpected. The reversing layer lies between two agitated structures. Beneath are the photospheric clouds, rent and whirling under the stress of cyclonic disturbances; above, the chromospheric flames, driven hither and thither by influences of fantastic violence. Yet a region of peace seems to intervene. The Fraunhofer lines indicate a steady vertical circulation, but scarcely ever a temporary commotion. By a rare exception, Father Fényi observed at Kalocsa, 27th July 1887, the dark C in the neighbourhood of a spot-group, displaced alternately towards the blue and the red, indicating, he supposed, a powerful disturbance of the reversing stratum by an irruption of

[1] *Comptes Rendus*, 9th July 1894.

hot hydrogen.[1] Such invasions of its precincts, however, are under the ban of some prohibitive decree, or they encounter unknown difficulties. They occur, at any rate, with remarkable infrequency.

The reversing layer is heated from below, and gravitates downward. Thermal equilibrium is doubtless maintained by the convective transport of material, but the due effects of superincumbent weight are unapparent. Evidence is not indeed wanting of *some* increase of density with descent, but of an increase relatively insignificant. Gravity at the sun's surface possesses nearly twenty-eight times its terrestrial power; hence a true solar atmosphere should double its density with each furlong of approach to the sun's surface,[2] and the total increase of pressure in an envelope five or six hundred miles deep would be "inexpressible by numbers that have name." Actually there is, at the most, a quintupling of pressure. This formidable discrepancy is altogether unexplained. We are debarred by it from considering the reversing layer to be in statical equilibrium. Its successive strata do not rest one upon the other under the sole dominion of gravity. Some counteracting influence is brought to bear. This problem of *levity*—so to call it—is one that perpetually recurs in studying the solar surroundings.

[1] *Publicationen des Haynaldschen Observatoriums*, Heft vi. p. 15, 1892.

[2] See *Knowledge*, vol. ix. p. 49 (E. W. Maunder).

# CHAPTER V.

## HYDROGEN, HELIUM, AND CORONIUM.

THREE tenuous gases—hydrogen, helium, and coronium—are of essential importance in solar physics. The first plays also a leading part in terrestrial and vital economy. The second exists on the earth merely as a chemical curiosity. The third must for the present be classed as an exclusively solar product.

Solar hydrogen was discovered by Ångström in 1862. He recognised it by the identity of its three least refrangible rays with the Fraunhofer lines C, F, and G[1] (now designated H$\alpha$, H$\beta$, and H$\gamma$), to which, in 1865, he associated the indigo line $h$ (H$\delta$). A fifth line (H$\epsilon$), photographed by H. W. Vogel in 1879, is situated quite close to the calcium H—so close that, like Teucer behind the shield of Ajax, it lies concealed, in the sun, under covert of its neighbour's broad shadow, if indeed it be present in the Fraunhofer spectrum at all; for it is so effectually hidden that the point remains uncertain. Shortly afterwards, Sir William Huggins's spectrographic investigations of Sirian stars gave the key to the true character of the hydrogen emissions. Nine ultra-violet lines came out on his plates, and their rhythmical arrangement at intervals continually lessening upward left no doubt of their forming a connected series. That this included the visible lines was manifest at sight. Its law was stated by Balmer in 1885.[2] The relations expressed by his formula are not those of wave-*lengths*, but of their reciprocals, wave-*frequencies*. These

[1] The third hydrogen line (H$\gamma$), often called "G," is adjacent to the band at $\lambda$ 431 named G by Fraunhofer.

[2] *Wiedemann's Annalen*, Bd. xxv. p. 80.

quantities obviously bear to each other an inverted proportion. Deep crimson light, for instance, consists of undulations about twice as long as those of violet light; only half as many of them, accordingly, enter the eye in a given time. A doubled length corresponds to a halved frequency, a tripled length to a frequency of one-third, and so on. Now oscillation-frequencies are, for several reasons, more important natural constants than wave-lengths; hence until they were made the basis of investigation, no real progress was effected in the detection of spectral series.

Balmer's law has the following form: $N = N_0 - \frac{4N_0}{m^2}$, where N is the wave-number $\left(\frac{1}{\lambda}\right)$, $N_0$ is a constant to be determined by trial, and $m$ is any integer greater than 2. By assigning to $N_0$ the empirical value 27418·75, the places in the spectrum of each individual ray emitted by hydrogen may be calculated with approximate accuracy. That of C ($H\alpha$) corresponds to $m = 3$, and the series has been photographed up to $m = 34$, its constituent lines growing fainter and more crowded as the scale is ascended. They approach, in fact, with the increase of $m$, indefinitely near to a definite limit, marked by the constant $N_0$ minus 0 (the second term having disappeared). This limit, known as the "convergence frequency," is a distinctive feature of spectral series.

Many have contributed to their elucidation. Johnstone Stoney,[1] Alexander Herschel,[2] Hartley,[3] and Cornu[4] prepared the ground, and the subject was treated, in its larger bearings, and with more definite results, by Liveing and Dewar,[5] Schuster,[6] Rydberg of Lund,[7] Runge and Paschen[8] of Hannover, Kayser[9] of Bonn, and Ames[10] of Baltimore. Their labours have been unexpectedly successful in educing partial order out of all but total emissive confusion. Harmonic series of identical type were marshalled from promiscuous throngs of

[1] *Phil. Mag.* vol. xli. p. 294 (1871).
[2] *Trans. Royal Soc. of Edinburgh*, vol. xxxii.
[3] *Journ. Chem. Society*, vol. xliii. p. 390.
[4] *Journ. de Physique*, t. v. p. 341 (1886).
[5] *Phil. Trans.* vol. clxxiv. p. 187.
[6] *Nature*, vol. lv. p. 200.
[7] *Phil. Mag.* vol. xxix. p. 331; *Wied. Ann.* Bd. lii. p. 119.
[8] *Ibid.* Bd. lxi. p. 641.
[9] *Berlin Abhandl.* 1890
[10] *Phil. Mag.* vol. xxx. p. 33 (1890).

rays, and their association into sets of three, or even into double sets of six, simultaneously given forth by a single element, proves the extraordinary complexity of the molecular systems through the movements of which they originate. That some of these movements are of an orbital nature is strongly indicated, and they not improbably show perturbative effects analogous to those manifested in lunar and planetary revolutions. "The final impression," M. Balmer writes,[1] "which our mind involuntarily receives in contemplating these fundamental relations is that of a wonderful mechanism of nature, the functions of which are performed with never-failing certainty, though the mind can follow them only with difficulty, and with a humiliating sense of the incompleteness of its perception."

Until 1897 the spectrum of hydrogen was thought to be of unique simplicity. It apparently consisted of one individual series resembling that formed by a musical note and its overtones. No outstanding lines interrupted the perfect regularity of the progression. All this, however, was changed by Professor Pickering's discovery, in a few peculiar stars, of a second hydrogen series.[2] It is associated with the first in such a manner as to indicate that both are subordinate to a principal series, the three together forming a triple group on the normal pattern. Of the principal series, one member has been probably identified as a blue band in certain "bright-line" stars,[3] the rest being placed inaccessibly high up in the ultra-violet. They would be cut off by atmospheric absorption. None of the new hydrogen rays occur in the sun, and none have, so far, been rendered visible in the laboratory, possibly because the temperatures available are inadequate for their production. This indeed is a matter of conjecture; what is certain is that hydrogen affords the only known example of a spectral series capable of isolation from its fellows. Here evidently we have a clue to some specialty of intimate structure, the guidance of which may lead to surprising disclosures.

Hydrogen has other singularities. In some respects it is solitary among the elements. The "periodic law," by which

[1] *Astroph. Journ.* vol. v. p. 209.
[2] *Ibid.* vol. v. p. 92; Kayser, *ibid.* pp. 95, 243.
[3] Rydberg, *ibid.* vol. vi. p. 233.

their properties are connected with their atomic weights, does not apply to it. Chemically and electrically it behaves as a metal; reduced to the liquid state, however, it definitely ranges itself with non-metals. Its condensation is effected with the utmost difficulty, physical and mechanical agencies being only just competent to vanquish the elasticity of this lightest of terrestrial substances. But what force can barely compel, affinity readily obtains. United to oxygen under the form of water, it can exist as a liquid up to a temperature of 100° C., and it is of all gases the most readily "occluded." Imprisoned thus in metallic masses, it remains inert for unlimited periods, but recovers freedom and activity by heat. Meteoric irons bring to the earth no inconsiderable supply of occluded hydrogen, and palladium can take it up to the extent of six hundred times its own volume. In this quasi-combination it is, by a curious anomaly, six times denser than when liquefied by sheer cold.[1]

The volatility of hydrogen perhaps transcends the earth's power of control. By a necessary consequence of the kinetic theory, adverted to by Dr. Johnstone Stoney in 1870,[2] light gases in a free state can be permanently retained only by massive globes. For atmospheric particles no sooner attain a speed just overbalancing the holding power of gravity than they irrevocably fly off into space, and the process being continued unintermittently, eventuates in the total dissipation of the envelope they once constituted. It is, however, a matter of some delicacy to discriminate between the gases that may escape from any individual planet and those that must remain. According to a recent calculation,[3] the earth could now maintain a hydrogen atmosphere virtually without waste; but in former ages, when the agility of the gaseous molecules was quickened by heat, the strength of its grasp upon them must have been insufficient for their lasting retention. This was nevertheless effected by their reduction to the liquid state in the form of water. The presence of an excess of oxygen hence saved terrestrial hydrogen.

Only the four lowest members of the hydrogen series

[1] Dewar, *Trans. Chem. Society*, 1898, p. 535.

[2] *Astroph. Journ.* vol. vii. p. 25. The idea seems to have been anticipated by Waterston in 1845. E. Rogovsky, *ibid.* vol. xiv. p. 251, *note.*

[3] S. R. Cook, *ibid.* vol. xi. p. 36; but cf. Stoney, *ibid.* pp. 251, 357.

show dark in the sun.[1] The absence of the higher rays is enigmatical. All are ablaze in the chromosphere; but the chromospheric gases emit sensibly as much light as they stop. In the reversing layer it would then seem that hydrogen glows so imperfectly as to emit vibrations of no more than four or five qualities, the upper "notes" being somehow quenched. It might be supposed that the temperature there is too low for their production, were it not that they have been photographed from vacuum tubes held, on good grounds, to be cool relatively to the electric arc. The true explanation is probably to be found in the heterogeneous composition of the stratum in question. Intermixed particles of different kinds of matter mutually check each other's oscillations, and those of shortest periods are the most susceptible to this adverse influence. Its nature and the laws of its action remain obscure, but much may be learned about them by careful experimental inquiry.

A similar anomaly is more markedly visible in the case of helium. This gas exists near the sun in scarcely less profusion than hydrogen, yet the Fraunhofer spectrum includes no trace of its action. Absorptive nullity is not a quality inherent in the substance, as we shall see presently; hence it probably depends, like the partial inertness of hydrogen, upon conditions present in the reversing layer.

Until March 1895 helium was known only as a chromospheric element. A bright yellow ray at $\lambda$ 5876, distinguished as "$D_3$," because it forms a trio with the sodium pair $D_1$ and $D_2$, was noticed in the prominences uncovered during the eclipse of 18th August 1868, and can always be observed spectroscopically at the edge of the sun. But the substance emitting the yellow ray lay outside the range of our acquaintanceship, and seemed unlikely to be brought within it. That contingency, nevertheless, came to pass. In the course of a search for compounds of argon, Professor Ramsay, at the suggestion of Professor Miers, fortunately examined the reputed nitrogen occluded by the Scandinavian mineral "clevite."[2] This velvety-black stone, remarked as peculiar by Nordenskiöld and

[1] Rowland observed in his photographs some "thin haze," which he regarded as possibly due to diffuse absorption by four ultra-violet hydrogen lines, but the connection is very doubtful. Huggins, *Atlas of Stellar Spectra*, p. 150.

[2] *Chemical News*, 29th March 1895; *Nature*, 19th December 1901.

analysed by Cleve, is a kind of pitch-blende, composed of uranate of lead mixed with rare earths. The gas evolved from it at University College gave a brilliant spectrum, in which the prominence-line $D_3$ shone conspicuous. Helium was indeed captured! A beautiful confirmation of the identity was soon afterwards afforded. The golden line seen in the laboratory was perceived by Runge to have a faint close companion, and he declared that, unless the solar $D_3$ were also double, clevite-gas should be regarded as different from helium.[1] The challenge was taken up on both sides of the Atlantic. Professor Hale on 20th June, and Sir William Huggins


FIG. 5.—Diagram of the Helium Spectrum.

independently on 10th July, succeeded in resolving the prominence-ray into a delicate, unequal pair, and our possession of helium as a truly indigenous element was rendered incontrovertible.

Meantime sundry other leading chromospheric rays—four especially, coloured deep red, green, blue-green, and intense violet[2]—had been recognised in the complex spectrum of clevite gas.[3] The task, however, of reducing its tangled rays to harmonic order seemed desperate until it was performed. Without exception, they ranged themselves, at the bidding of MM. Runge and Paschen, into six related series (see Fig. 5). These form two sets, each consisting of a surbordinate pair drawing together towards a common limit in the ultra-violet,

[1] *Nature*, 6th June 1895.

[2] Their wave-lengths are λλ 7066, 5016, 4472, and 4026.

[3] Lockyer, *Nature*, 3rd October 1895.

with a principal series "leaping over the other two in large bounds," and ending in the more refrangible part of the spectrum.[1]

Not only did Runge and Paschen's formula (which may be regarded as a modification of Balmer's law for hydrogen) include all the perceptible emissions of helium, but it intimated the presence of others beyond the reach of ordinary observation. Each of the principal series, it was inferred, should own a "leader line" far down among the heat rays, and with the aid of the bolometer the prediction was strictly verified. Thus "the actual spectra" (as Mr. Maunder remarked) "corresponded to the theoretical, and were complete from their rise far in the obscure regions of the infra-red till they died away in the darkness which lies on the other side of the visible spectrum."

Their number, however, suggested a twofold origin, since there was then no precedent for assigning more than three series to a single substance. Clevite gas was accordingly regarded as a mixture of two solar elements, distinguished as "helium" and "parhelium," the rays of the former, like $D_3$, being all double, those of the latter single. Each set of three series was, in fact, "analogous to the complete spectrum of a distinct element." Yet parhelium has failed to make good its footing in either cosmical or terrestrial chemistry. Attempts to isolate it have entirely failed, and the spectroscopic argument for its existence collapsed with the discovery that oxygen, no less than clevite gas, claims six series, which are certainly inseparable, and represent in combination the vibrations of perfectly similar, highly intricate molecular systems. "Parhelium" may then safely be treated as fictitious. Clevite gas, or mineral helium, is the identical undiluted material of prominences. The hypothetical companion-stuff exists neither in the sun nor upon the earth.

The qualities of helium are most unusual. Like argon, it is monatomic; its ultimate chemical units are the same as its ultimate mass-units. This inference is based upon the heat-relations of the substance. Its vapour-density is hence

[1] Runge and Paschen, *Nature*, 26th Sept. 1895; *Sitzungsberichte Berlin Akad.* 20th June 1895; *Astroph. Journ.* vol. iii. p. 4; Maunder, *Knowledge*, vol. xix. p. 285.

only half its atomic weight; for the molecule of helium possesses nearly double the mass of the hydrogen molecule; and it is, by hypothesis, indivisible, while that of hydrogen includes two combining atoms. But helium has no "atoms," or rather its molecules *are* its atoms. Its chemical equivalent is accordingly 3·96 on the hydrogen scale. A value indeed rather nominal than real, since helium is devoid of sensible affinities. It enters into no combinations. It again resembles argon in being a "rogue" element. To both equally, one of the ordinary properties of matter is wanting. They form with three other inert gases a class apart as "non-valent" substances.[1] In choosing its mineral cloisters, helium showed, nevertheless, some original preferences. The heavy metal uranium has a special attraction for it, and it is constantly associated with rare earths. Once released, however, it can scarcely be re-incarcerated. Mr. Tilden's experiments led him to conclude that helium-yielding rocks must have been primitively charged under a pressure of several hundred atmospheres.[2] The earth may in those early days have possessed a vast helium-envelope, since dissipated in space. Opinions differ on the subject,[3] and data for precise calculations are wanting. But the probability is strong that the helium now sparsely lurking on our globe is a mere remnant of a far ampler store, which terrestrial potencies, whether gravitational or chemical, were incompetent to hold.

Helium scarcely retards the passage of light. Its refractive index, which is the smallest known, is expressed by the fraction 0·146, those of air and hydrogen being respectively 1·0 and 0·5. Still more unexpected than its low refractivity, is its high conductive power for electricity. Professor Ramsay ascertained that the "sparking distance" through helium at atmospheric pressure is nearly 300 millimetres, while the same current is stopped in hydrogen by a gap of 40, in oxygen by a gap of just 24 millimetres.[4] Another surprising property of this gas is its abnormal faculty of diffusion. It has a rate of self-dispersion ten times that of

[1] Ramsay and Collie, *Proc. Royal Society*, vol. lx. p. 56.
[2] *Ibid.* vol. lix. p. 222.
[3] See *Nature*, 17th and 24th May 1900 (Cook and Johnstone Stoney).
[4] *Fifth Robert Boyle Lecture*, 2nd June 1895.

hydrogen, or fifteen times what, by Graham's law, it ought to be. On the other hand, it has the lowest solubility on record;[1] water absorbs it in evanescent quantities. This led to the anticipation, amply justified by experience, that helium would prove to be one of the most obstinately gaseous bodies in existence. It has not indeed yet (October 1902) surrendered to the compulsion brought to bear by Professor Dewar in his memorable researches at low temperatures. Still, the cooling efficacy of liquid hydrogen evaporating under exhaustion may be expected finally to overcome its all but invincible recalcitrance, and the "salamander gas" of the chromosphere will assume the guise of a frigid fluid boiling five or six degrees above absolute zero.

The reversing layer—properly so-called—emits apparently no helium rays. A reason for their absence has been already suggested, and is tolerably obvious. They are extremely sensitive to damping influences. Foreign admixtures readily occasion their suppression. Thus 10 per cent of helium just shows spectroscopically in hydrogen, and that only if the pressure in the tube is very low; while one part of hydrogen in 100,000 of helium glows manifestly when the current is made to pass.[2] Nitrogen has a similar adverse effect upon helium-radiation, which would, however, gain relatively in strength with diminution of pressure in ascending through the reversing-layer into the chromosphere.

Of the chief coronal ingredient no terrestrial trace has yet been found. A bright green ray observed during total eclipses is its only assured badge, for eight or nine other more refrangible associated rays may quite possibly emanate from different substances. As the leading gaseous constituent of a structure on the borderland of nothingness, coronium must be an unimaginably subtle form of matter. It exists in prodigious volumes near the sun, rising to heights altogether inaccessible to hydrogen or helium, yet under conditions differing from those of an ordinary atmosphere. Successive coronal strata are not mutually superincumbent. There is no sign that their density increases downwards. The characteristic green line is no less fine and sharp given out by the

[1] Ramsay, Collie, and Travers, *Journ. Chem. Society*, 1895, p. 697.

[2] Collie and Ramsay, *Proc. Royal Society*, vol. lix. p. 264.

inner than by the outer corona. No reversal of it has ever been detected. There is no corresponding Fraunhofer line. Thus the substance most plentifully present about the sun is, by a strange anomaly, absolutely passive as regards its light. This is most probably a result, not of any specific incapacity, but of the peculiar state in which it subsists. The real qualities of coronium, however, and its entire spectrum can only be ascertained by laboratory investigations. That these will ever become practicable it would be rash to assume, but it is permissible to hope. There seems, at any rate, no valid reason why coronium should not be added to the number of unearthed or frozen-out recondite gases. The former possession by our planet of a coronium-atmosphere may be plausibly surmised. But it most likely vanished still earlier than that of helium. Had its material been endowed with chemical affinities, some compound or compounds should have preserved it more or less abundantly. It would have been detained, as hydrogen was detained in water, and kept available for our late acquaintanceship. Since no compound of the kind appears to exist, coronium presumably resembles helium in being "non-valent."

# CHAPTER VI.

## THE PHOTOSPHERE AND ITS DUSKY VEIL.

THE sun is virtually bounded by a spherical envelope of intense lustre. What lies outside is negligible in mass and function. What is hidden within has its energies concentrated, so to speak, on the maintenance of the "photosphere" at the highest point of radiative efficiency. This implies enormous internal activity, the slackening of which would be the prelude to speedy extinction. The materials of a self-renewing stratum of concentrated emission are necessarily in a state of flux. Each constituent particle, as it delivers up its store of light and heat, becomes instantaneously effete, and is replaced by another. Charging and discharging processes pursue a ceaseless round, ceaseless, that is to say, until the growth of viscosity fatally impedes them. When that time comes, convection-currents cease to flow, superficial cooling advances rapidly, and the sun-like stage terminates. The epoch of inertness must in fact arrive when, for a circulatory, a fixed surface is substituted. During some long antecedent period, again, the same body was presumably too rare to be definitely limited, and might fitly be designated a nebula. So that a "sun" is definable as a gaseous mass clothed with a pellicle of dazzling luminosity, and organised for long continuance in the capacity of a distributor of light and heat.

The shining pellicle of our sun is, to all appearance, of a cloud-like nature. It is a locus of condensation, where up-rushing gases, chilled by expansion, momentarily change their state, and thus acquire the power of suddenly parting with their stored energy. The "mottlings" of the photosphere mark visibly, perhaps, this rapid course of interchange,

brilliant floccules denoting regions of *arterial* ascent, dusky tracts those of corresponding *venous* descent. That it is accompanied by violent turmoil, the evidence of the camera shows conclusively. The reticulated areas are highly evanescent. Ridges and brilliant cumuli, some hundreds of miles in extent, form only to be swept away. "When we come to study the minute details of the granulations," Professor Young writes, "we find movements at the rate of a thousand miles an hour to be the rule rather than the exception."[1]

Since photospheric light is purely continuous, photospheric chemistry remains a *terra incognita*. Only conjectures are possible regarding the kind of matter present in the solar condensations. The idea that they may be formed of carbon, started by Dr. Johnstone Stoney in 1867,[2] is still very generally entertained. It is indeed hampered by difficulties at present insurmountable; but the same may be said of every other hypothesis on the subject. Carbon was recommended for the position assigned to it by its refractoriness to heat and by its great radiative power. Lampblack, we need hardly say, is, in this latter respect, the standard substance. An unfavourable peculiarity, on the other hand, is its inability to exist as a liquid under conditions at all likely to be realised in the sun. Carbon has no fusing-point in the ordinary sense. At a temperature of about 3500° C. it sublimes without melting. Preparatory to crystallising as diamond it perhaps liquefies through the incomparable stress of molecular forces, but the process is transitory and obscure. It has never been observed; it is only reasonably supposed to take place. Moreover, at or near the photosphere, pressure of the required intensity certainly does not exist. The cumuli forming it should then consist, not of carbon droplets, but of carbon dust, and the analogy with terrestrial clouds would disappear. A still more serious objection is that carbon volatilises at a temperature far below that of the photosphere. Nor are we acquainted with any kind of matter the condensation of which might be thought of as possible under the conditions there prevailing.

The question of temperature is fundamental in solar physics.

[1] *The Sun*, p. 110, edit. 1897.

[2] *Proc. Royal Society*, vol. xvi. p. 29.

Everything that regards the nature, structure, and innate activity of the solar globe depends upon the answer furnished to it. And of late the answers have become much more plausible than those discordant to the extent of some millions of degrees arrived at thirty years ago. The main cause of this wide uncertainty lay, not in the actual measurements, which can be made sufficiently precise, but in the failure to establish on secure grounds some definite relation between temperature and radiation. There is no doubt that thermal outflows increase far more rapidly than the accompanying thermometric rise—that the heat received at a distance corresponds, in an augmented proportion, to a gain of heat at the source; but the correspondence has, until lately, been expressed only by empirical rules, not implicitly or unconditionally to be trusted. Boltzmann,[1] however, supplied an *ex post facto* theoretical basis for a law published by Stefan of Vienna in 1879, according to which radiation grows as the fourth power of temperature. Its agreement with facts, so far as they are available, is besides tolerably close. Yet the security is precarious that it continues to match them in regions of cosmic heat, unattainable by experiment. It was, however, employed by Messrs. Wilson and Gray, with some modification and with excellent results, in their authoritative determination of the sun's temperature.[2]

They adopted a method of direct observation, involving the fewest possible uncertainties of principle. Sun-heat, allowed to fall upon a "radio-micrometer"—an instrument of extreme sensitiveness invented by Professor Boys—was measured by the "balancing" of its effects against those of a strip of platinum heated to a known pitch. This gave the means, by the aid of Stefan's law, of translating them into terms of temperature. Allowance had then to be made for a double absorption, first in the sun's, again in the earth's atmosphere. That only a fraction of the heat emanating from the solar condensations reached the apparatus in the West Meath observatory was unmistakable; how large a fraction was less easy to decide. Langley finds that the intensity of radiation at the centre of the disc is reduced near the limb

[1] Scheiner, *Strahlung und Temperatur der Sonne*, p. 27.

[2] *Proc. Royal Society*, vol. lviii.

by one-half,[1] and the total loss is estimated by Wilson and Rambaut at one-third of the whole.[2] Hence the sun's thermal power would be one and a half times greater than it is if the emitting surface were stripped of its absorbent covering, and the correction of temperature demanded by its action amounts to at least 1000° C.

The despoiling effect of our own air has next to be considered. It is very large, and so are the discrepancies in its valuation. Rosetti of Padua, who in 1879 determined the temperature of the sun to be 20,000°,[3] concluded for a zenithal heat-stoppage of 29 per cent; Langley estimated it at 41; Knut Ångström[4] in 1890, laying stress for the first time upon the thermal opacity of the carbonic acid ingredient of the atmosphere, obtained 64 per cent as the ratio of absorption. This seemingly authentic result, namely, that only 36 per cent of the heat rays striking the earth vertically are transmitted to its surface, was provisionally admitted by Wilson and Gray, and after having made careful allowance for various kinds of possible error, they arrived in 1894 at an effective solar temperature of 8700° C. Substituting Langley's value for terrestrial atmospheric absorption, and working up fresh experimental data, Mr. Wilson in 1901 reduced this figure to 6590°,[5] which probably underestimates the truth. At some such inconceivable degree of heat the undimmed photospheric clouds glow.

This is not all. The value just given belongs to an ideal stratum in the sun. It stands for the "effective," not the actual temperature—the temperature, that is to say, which should be attributed to a surface of standard radiative capacity sending out the measured quantity of heat. Now it is certain that the photosphere falls very far short, in emissive power, of its imaginary substitute. There is no such thing in nature as a "perfectly black body," or its correlative, a perfect radiator, the efficiency even of lampblack being only six-tenths of what it is assumed to be for purposes of calculation. And the sun is unlikely to be as good a radiator as lampblack. It must

[1] Young, *The Sun*, p. 302. [2] *Phil. Trans.* vol. clxxxv. p. 396.
[3] *Phil. Mag.* vol. viii. pp. 324, 550.
[4] *Wiedemann's Annalen*, Bd. xxxix. p. 309.
[5] *Proc. Royal Society*, 12th December 1901.

then be hotter in proportion to its inferiority, but to what extent it falls short of the ideal standard remains undetermined. It must also be very unequally hot. The brilliant granules giving its flocculent appearance to the photosphere radiate much more intensely than the gray interspaces. Hence computed temperatures represent an average higher than prevails in some formations, lower than is assignable to others. It is noticeable that several corrections based upon recent improvements in experimental data tend to enhance our conception of the tremendous energy of solar heat.

Le Chatelier's method [1] of employing the intensities of selected rays in various light-sources as a criterion of temperature gave 7600° C. for that of the sun (uncorrected for solar absorption). It is, however, of doubtful validity. A parallel line of research was opened by Langley's establishment of the principle that temperature is connected by a definite relation with the wave-length of maximum energy in the spectrum of a radiating body. Divergent views, nevertheless, prevail as to the *form* of the relation. Michelson [2] and Rubens [3] agree that the wave-length of most powerful emission varies in length inversely as the square root of the temperature, while Paschen and Wien [4] maintain that the simple inverse ratio tallies more closely with facts. The outcome in determinations of the sun's heat differs of course vastly with the law chosen. From Michelson's, H. Ebert deduced in 1894 a temperature of 40,000° C., but added the qualifying remark, "The parts of the sun to which this value applies belong to the more interior regions; they are at any rate deep under the reversing layer, and therefore probably below the photosphere." [5] Now subphotospheric heat may be of almost any intensity; hence the result, although not very informing, is safe to be in some sense correct. Paschen, on the other hand, obtained the low value of 5130°. It might be added that the law upon which he relied is suspiciously simple, "in view of the known complexity in the radiation of a solid body, and the various rates of increment with temperature attaching to different

[1] *Comptes Rendus*, t. cxiv. p. 737, 1892.
[2] *Journ. de Physique*, t. vi. p. 474, 1887.
[3] *Wied. Ann.* Bd. liii. p. 284, 1894.
[4] *Astroph. Journ.* vols. ii. p. 202, x. p. 40, xi. p. 288. [5] *Ibid.* vol. ii. p. 57.

rays."[1] It seems to be one of those formulæ which cannot be trusted far out of sight. They are *not true enough* to bear extension into regions beyond experience. Useful over a moderate compass, they prove treacherous adjuncts to investigation. Difficulties, indeed, all but insuperable hamper attempts to infer the solar temperature from comparisons of spectral energy-curves. Unexpected peculiarities are found to characterise the modes of emission of solid bodies. Even continuous spectra are to some extent distinctive. Thus the same quantity of energy is very differently distributed in the rays sent out respectively by polished and lampblacked platinum, by carbon filaments, copper, and iron oxides; while with an equal increase of energy, the distribution becomes diversely modified for each substance. For each, that is to say, the maximum ordinate of the energy-curve creeps upward at a different rate. In the absence, then, of precise knowledge as to the composition and condition of the photosphere, inquiries as to its temperature, based on this principle, are futile. We should first need to be acquainted, in Professor Very's words, with "the selective radiating power of the solar photosphere."[2] Generalisations are here eminently unsafe, since laws of radiation derived from the experiments with one kind of material are by no means certain to prove applicable to others. Besides, the "absolute solar spectrum" (as Langley calls it) cannot be directly observed, and the shape of its representative curve is most materially altered by the effects of absorption in the solar atmosphere.

On the whole, the straightforward plan of attack on the problem of the sun's heat seems the most promising. Messrs. Wilson and Gray's practical operations left little room for improvement, and the uncertainties affecting their final result will gradually diminish with the progress of other kinds of research. As higher temperatures, for instance, are brought under command, the range allowed to perilous processes of "extrapolation" can be restricted. And improvements, sure ere long to be realised, in the value assignable to telluric atmospheric absorption, will effectually reduce the

[1] F. W. Very, *Astroph. Journ.* vol. ii. p. 317.
[2] *Ibid.* vol. iv. p. 44.

marginal errors attached to present estimates of the *primitive* heat-power of the sun.

Fluctuations in the sun's heat-power must be regarded as possible, and they might be either irregular or periodical. Indeed, the superposition of both kinds of change would perhaps be more likely than the occurrence of either separately. Their detection would, in any case, be extremely difficult, although it is not, in Messrs. Wilson and Gray's opinion, to be regarded as hopeless. The required measures would be simply differential; and differential measures escape many of the snares that hamper the execution of absolute measures. But comparisons in this matter are rendered almost nugatory by inconstancy of weather. Variations in the "solar constant,"[1] even if real, would probably be masked by local and temporary changes in the diathermancy of the air. Professor Very holds that "under these circumstances refinements in actinometry are of small avail,"[2] and he suggests "that the problem will have to be solved entirely by meteorological methods."[3] "If temperature and humidity observations could be collated from the logs of vessels crossing the torrid zone, estimates of oceanic evaporation from day to day, combined with rainfall measures, might lead," he believes, "to the detection of the variation of solar radiation." But the chance of their doing so appears, all things considered, to be incalculably small. The elements of disturbance are too numerous and too strong to permit the emergence of the slight residual effects looked for. Far preferable appears Piazzi Smyth's plan of earthing thermometers deeply enough to be inaccessible to superficial vicissitudes of temperature. And it can scarcely be without significance that the readings of those buried on the Calton Hill showed oscillations coincident in period with the sun-spot cycle.

[1] The "solar constant" is the number of units of heat per unit of area which would be received in unit of time by the earth's surface if its atmosphere were removed. The most approved value is three (small) calories per square centimetre per minute, a "small" calorie being the quantity of heat requisite to raise one gramme of water one degree centigrade.

[2] Hence Savélieff's experiments, according to which the solar energy progressively augmented with the increase in the number of spots in the years 1890, 1891, and 1892, are suggestive rather than conclusive (*Comptes Rendus*, t. cxviii. p. 62, and *Astroph. Journ.* vol. xiii. p. 346).

[3] *Astroph. Journ.* vol. vii. pp. 255, 264.

Absorption in the sun's atmosphere may also prove to be variable. And here again differential observations should suffice to test the question. They were undertaken by Wilson and Rambaut in 1892, but relinquished after one series had been made. The method employed was to pass an image of the sun across the radio-micrometer, while the motion of a spot of limelight, reflected from the mirror of the instrument, recorded the changing amounts of heat received from the different parts of the disc. The intention was to obtain such "curves of absorption" frequently throughout an eleven-year cycle, and thus determine the question of concurrent fluctuations in depth of the absorbing envelope. "If we find," the authors wrote, "that such changes are taking place, as would be shown by the alteration in the ratio of the heat from the limb and centre of the disc, we think it will be quite possible, by an investigation of the co-ordinates of these curves, to determine the change in the value of the solar constant."[1]

This theoretical possibility, nevertheless, is still a long way from realisation. Divers indications lead almost irresistibly to the conclusion that the sun is hotter at certain times than at others; and Professor Young counts it as "one of the most important and difficult problems of solar physics now pending to determine the actual amount of these variations and ascertain the laws that govern them." But they are, as we have partly seen, disguised by manifold complications.

The one clear upshot of inquiries into the temperature of the sun is to show that it stands high above the boiling points of the most refractory among the chemical elements. The fact is embarrassing, but cannot be evaded. Apart from its consideration, no theory as to the nature of the photosphere is of the slightest value. And it is no easy task to frame one bringing it into harmony with other circumstances equally well assured, and equally rigid in their consequences. Three alternative hypothesis may be said to exhaust the possibilities of the subject. They are as follows:—

1. The photosphere is a surface of condensation for unknown materials capable of maintaining the liquid or solid state at a transcendent degree of heat.

[1] *Proc. Royal Irish Acad.* vol. ii. p. 299, third series.

2. It is a surface of condensation for known materials under unknown conditions.

3. It is no true surface of condensation, the substances composing it being, although viscous, still vaporous.

Now each of these explanations is largely an appeal to ignorance, and so far scarcely deserves to be ranked as an explanation at all. Yet one of them must be fundamentally true. The first may be dismissed as contradictory of a strong consensus of evidence. The third involves glaring incongruities, both with what can be seen and with what must be inferred. There remains only the second. We seem bound to adopt the view that the sun is veritably clothed in a kind of cocoon—a web of incandescent filaments. It is perhaps of mixed composition. The surface is irregular. It comprises "fleece-like floors" at apparently different levels. Possibly they represent the successive condensations of various substances—silicon, carbon, titanium, vanadium, platinum, to mention a few of those most resistant to heat. The diversity of their emissive powers might contribute to produce the *tonings* brought out in photographs of the disc, and the arrangement would be analogous to the surmised replacement in our upper air of aqueous by carbonic acid cloud-fields. But the postulated "unknown conditions" needed to enforce condensation at the enormous temperature of the photosphere may long continue to baffle the scientific imagination.

A darkening of the sun's disc towards the limb is obvious telescopically, and conspicuous photographically. Its amount, measured by Bouguer in 1729, formed the basis of Laplace's calculation that the arrest of light indicated was no less than eleven-twelfths of the entire. The data were correct, but the result, owing to certain mistaken assumptions, was greatly in error. Modern authorities, nevertheless, are far from being unanimous on the subject. Pickering finds that the intrinsic lustre of the sun exceeds its apparent lustre four and two-third times; the disparity, according to Vogel, is about two-fold. There are, however, distinctions to be made. The absorption in the solar, as in the terrestrial atmosphere, is markedly selective. The brunt of its attack falls upon the most refrangible rays. Father Secchi noticed in 1870, and Professor Langley again in 1875, that the light from the limb

is, in consequence, tinged with chocolate brown, while that from the central parts of the disc seems bluish by comparison. This general indication was, in 1877, analysed by Dr. Vogel,[1] who, by detailed measurements with a spectral photometer constructed on the polarising principle, ascertained that 30 per cent of the red, but only 13 per cent of the violet marginal rays penetrate the solar atmosphere. Hence an alteration in tint corresponding in its mode of origin to the ruddy suffusion of the setting sun. Now Seeliger has pointed out that selective absorption implies a medium of high refractive power; but equivalent conditions might, according to E. von Oppolzer,[2] be supplied by "a rare atmosphere in which flying particles are suspended." It is, beyond doubt, an exceedingly shallow one. This was inferred by Vogel from the rapid degradation of light towards the edge of the disc, and it is rendered patent to sense by the brilliancy of facular summits, which, rising above the absorptive strata, shine unveiled against the dusky limb. Obviously, then, the darkening effect is produced in the immediate neighbourhood of the photosphere. It cannot be due to *cool* gases, and *hot* gases stop light distinctively in isolated beams. An alternative hypothesis was suggested some time ago by Professor Hastings of New Haven. The sun's so-called "atmosphere" is, in this view, nothing more than a smoke-laden stratum.[3] Minute solid particles of carbon or silicon, carried upward from the photospheric clouds, are the agents of obscuration. The assumption of a solar analogue to a London fog is certainly a daring expedient, yet none more satisfactory is at present available.

The sun's "veil" is indeed particularly difficult to fit in with the rest of its economy. It manifestly exists, and the position seemingly prescribed for it is between the photosphere and the reversing layer, although Dr. Scheiner prefers to place it in chromospheric regions.[4] In some torrid locality, at any rate, it exercises a kind of action characteristic of cool substances. Its composition out of refrigerated materials is

[1] *Monatsberichte*, Berlin, 1877, p. 104.

[2] *Astroph. Journ.* vol. i. p. 261.

[3] *Proceedings Amer. Acad. of Sciences*, 1880; *Amer. Journ. of Science*, vol. xxi. p. 41, 1881.

[4] *Strahlung und Temperatur der Sonne*, p. 49.

strongly indicated. The refrigeration, however, may be excessively transient as regards each individual particle, although permanent in their aggregate. The general effect is to diminish the sun's heat by one-third or one-half, and its light by fully two-thirds, with an attendant change to pale primrose of its original glacier-green tint.

Among the many enigmas of solar physics there is none more curious or more evasive than that which confronts us in this intimate appurtenance of the photosphere. Even the lines of approach to it are very few. Yet some are practicable, and almost untried. Researches of a special kind into the spectra of sun-spots should help towards its elucidation; still more, perhaps, careful spectroscopic comparisons with the obscurer interstitial spaces of the brilliant granules strewing the solar surface. If these are relatively dark through a mere lowering of temperature, then little can be learned from them in this connection. But if they are dark through increased absorption, it will be important to determine whether the absorption corresponds to that produced by the problematical "veil." Are they, in other words, sinks for solar *soot?* Do they mark the lines of subsidence of the same refuse materials which by their interposition dim and tarnish the shining face of the sun? A definite reply to the question would bring us preceptibly nearer to the goal of our inquiries into the nature of the sun's "smoke" envelope. What cannot be doubted is the importance of its function as a regulator of the sun's output of energy. This has for the first time been adequately discussed by Dr. J. Halm in a paper incorporated with the *Annals of the Royal Observatory, Edinburgh.*[1] His views on the subject demand careful consideration.

[1] Vol. i. p. 74, 1902.

# CHAPTER VII.

## STRUCTURE AND MOVEMENTS OF SUN-SPOTS.

A NORMAL sun-spot consists of a round black "umbra," garnished with a circumferential "penumbra." The chief member of the group shown in Fig. 6 is a good example.

FIG. 6.—Sun-spot photographed by Janssen, April 1, 1894 (from *Knowledge*, vol. xviii. p. 108).

The ground should be almost white, with the granular texture delicately indicated. The details of such objects, however, are seen much better than they can be photographed even by the consummate art of M. Janssen.

One of their characteristic features is the definite separation of their parts. The umbra does not merge into the

penumbra, nor the penumbra into the photosphere; the lines of demarcation are as sharp as the edge of a cascade. Their darkness is indeed accentuated by the enhanced brilliancy of the regions invaded by them. An immense area of disturbance usually surrounds an active spot, and this area of disturbance is also an area of actual elevation. A series of micrometrical measures carried out by M. Sykora of the Charkow observatory in 1895 showed that, as a very general rule, the sun's diameter is lengthened in the direction of a spot on the limb.[1] The fact is most significant, for it indicates relief of pressure as perhaps the cause, and certainly as an accompaniment of solar outbreaks, and thereby associates them with volcanic explosions. Now a region lifted is, on the sun, a region brightened, the effects of absorption diminishing with the rise of level. Hence the exceptional vividness of the photosphere in a spotted neighbourhood.

Faculæ gain higher altitudes, and are consequently still more lustrous. They are like the summit-ranges of a table-land. Their connection with spots is intimate, but not inseparable. Every spot, it is true, claims a retinue of faculæ; but faculæ exist abundantly where there are no spots. It is a moot point whether spots can come into being apart from preceding facular disturbance. "Which is the forerunner of the other?"[2] is a question not to be answered off-hand. As a rule, the embryo spot has apparent priority. The rule, however, is not invariable, and the priority recorded may often be illusory, faculæ being extremely evasive of observation. Their survival, on the other hand, after the openings enwreathed by them have closed, is obvious and constant. The complex relations of the two kinds of phenomenon must be unravelled before the nature of either can be thoroughly understood.

Photospheric structure is very curiously modified in the penumbræ of spots. The roundish granules of the unbroken surface seem as if drawn out into threads, which lie side by side, pointing radially inward, and overhang the umbra with ragged edges, compared by Dawes to those of an untrimmed straw-thatch. And the eaves of this luminous thatch are its

[1] *Astr. Nach.* Nos. 3330, 3410.

[2] Rev. W. Sidgreaves, *Astr. and Astrophysics*, vol. xi. p. 212.

brightest part, possibly because of the crowding together of materials forced into a narrow circular space. The whole effect suggests the subjection of viscid masses to a pulling action emanating from the centre of disturbance, by which they are stretched and *carded* like wool-flocks.

The umbra of a sun-spot shows a cloudy texture, markedly unlike the streaky aspect of the penumbra. This can be perceived, however, only when the seeing is exceptionally good. The ordinary impression is of uniform and very profound darkness. Contrast, indeed, greatly heightens this effect. The obscurity is only comparative. Mr. Evershed estimates the light-emissions from umbræ as varying from about one-twentieth to one-hundredth those of the dazzling photosphere,[1] and when intersected by the black advancing moon during the progress of a total eclipse they seem dully bright.[2] Yet with differences. They are rarely of the same tint throughout. Dawes perceived in 1852 a "black opening" in the umbra to be a characteristic of all well-developed spots. It can only, however, be discerned visually, and that by the aid of special precautions; the sensitive plate takes no notice of this deeper depth of shadow, which has, accordingly, received somewhat less attention than it deserves. Fortunately eye-and-hand portrayals still continue to be made, and they not infrequently afford valuable records of the Dawes phenomenon. M. de Pereira, a Portuguese observer at the Azores, wrote as follows of a group which came into view 20th April 1895: "The sense of a cavity in this spot is unmistakable, as though the crust of the sun were torn and scratched, and the black, or rather dark, under-skin were visible beneath. Definition on this day was the best I have ever seen, enabling me to make the smallest detail reliable. On the 24th, this same spot showed a conspicuous black hole in what I may call the centre of gravity, a dazzling white bridge crossing it from south to north-east, and a smaller one lying on the northern edge of the abyss, the brims being full of curiously intertwined points of photospheric matter."[3] The chief member of the splendid group visible in the sun's southern

[1] *Astroph. Journ.* vol. v. p. 250; *Observatory*, vol. xxi. p. 404.
[2] *Memoirs Royal Astr. Society*, vol. xli. p. 8 (Ranyard).
[3] *Memoirs Brit. Astr. Ass.* vol. v. p. 84.

hemisphere during the last half of February 1894 had also an inner nucleus,[1] and the same feature has been studied in numerous examples by Father Cortie, Mr. Maw, and others. It is commonly associated with the presence of "bridges," and both belong characteristically to the final stages of active spots. Bridge-building is preliminary to the indraught of luminous matter by which photospheric breaches are closed; it might be compared to the trickle under the dyke that preludes the rush of inundating waters. The process is a

FIG. 7.—Photograph of a Bridged Sun-spot, by Janssen (from *Knowledge*, vol. xiii. p. 74).

remarkable one. From abutments (so to call them) at opposite sides of the umbra, segments of light protrude; then at a given moment they unite with a leap or a flash, and the arch stands complete. A beautiful photograph by Janssen of a spot doubly spanned is reproduced in Fig. 7. But the ground is *altogether too dark*. The surface near the spot was dazzling, likewise the facular masses crossing the nuclei.

"On the negative," Mr. Ranyard wrote in describing it, "the brilliant bridge which stretches across the great spot is seen to break up into a number of distinct elongated masses," and these are evidently the "rice-grains" of the photosphere

[1] A. J. S. Adams, *Journ. Brit. Astr. Ass.* vol. iv. p. 203; E. Brown, *ibid.* p. 300.

laid end to end in single file for suspension above the abyss. This kind of structure is probably always present, although often imperceptible. Exceptional facilities are needed to bring out the finer details in spots. Thus Professor Young tells us that, on the rare occasions when powers of six hundred and upward could be profitably used with the twenty-three-inch Princeton refractor, he succeeded in resolving "the apparently club-like, almost bulbous ends of the penumbral filaments" into "fine sharp-pointed hooks, reminding one of the curling tips of flames, or grass-blades bending over. Ordinarily," he adds, "they are seen as club-like simply because of their brightness and the irradiation and diffraction effects of moderate-sized object-glasses." [1]

The connection of "bridges" with "black holes" was tentatively explained in a valuable paper presented by Father Cortie to the Royal Astronomical Society, 11th May 1900. He considers that the latter may be the portions of the umbra left uncovered by "faculous veils," which, extending from the penumbra, not unfrequently lighten up certain regions of nuclear gloom, leaving others more profoundly dark by contrast. Now the relationship between "veils" and "bridges" is obviously quite close. Both represent luminous invasions, although differently organised and conditioned, and both are heralds of decay. Their kinship is on occasions emphasised by the development of one from the other. Twice at least, in 1865 and 1866, the transformation into "roseate veils" of brilliant arches spanning the umbræ of spots was observed by Father Secchi at Rome.[2] He was quite positive about the colour of these "veils," which seems to intimate for them a gaseous nature, assimilating them to prominences rather than to faculæ.[3]

Sun-spots are rarely solitary. They ordinarily appear in clusters or processions, consisting of one or two dominating members and many satellites, down to mere umbral dots and penumbral scraps. Individual spots show endless varieties of conformation. The nuclei are often multiple; as many as nine umbræ have been seen within the compass of a single

[1] *The Sun*, p. 125. [2] *Il Sole*, p. 62, ed. 1884.

[3] Suffusions of dark red matter were observed in the umbræ of a multiple spot by E. S. Martin 17th September 1893, *Popular Astronomy*, vol. i. p. 91.

penumbra. Again, they become pear-shaped, or spiral, or caudate, as if through the action of stresses or twisting forces of an unknown character. The penumbra is equally subject

FIG. 8.—Sun-spot drawn by J. de M. Pereira, 18th June 1894.

to irregularities. It is sometimes a mere torn strip of fringe; half the umbra may be duly furnished with its *valance*, while the other half remains bare; or the umbra and penumbra may be disjoined by intruding photospheric matter. Fig. 8 shows a "fimbriated" spot from a drawing by M. de Pereira,

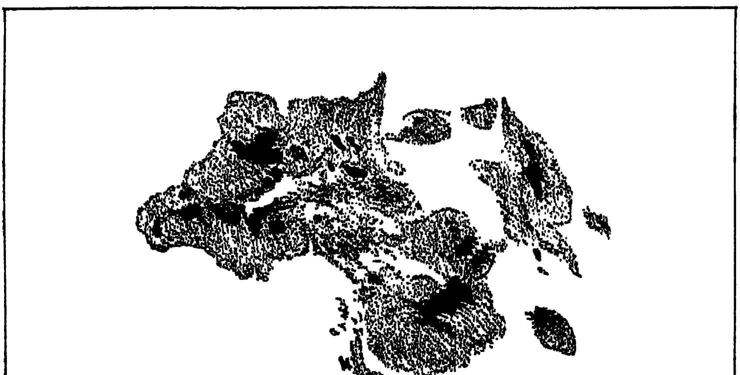


FIG. 9.—Group of Sun-spots drawn by Miss E. Brown, 15th August 1894.

the partially veiled and bridged umbra of which included two conspicuous black holes.

In Fig. 9 three "confluent" spots are represented, drawn

by the late Miss E. Brown, 15th August 1894. She described the group as covering "a vast extent of surface with a mass of nuclei and penumbra partially connected and very variable in form." A few hours later the largest nucleus had assumed a helical form, and seemed to be "throwing out feelers like a jelly-fish."[1] Strong hydrogen incandescence was spectroscopically perceived to be an accompaniment of these rapid changes. The great spot of September 1898 had in its declining stage a nucleus divided by intersecting bridges into three lobes; it assumed on 3rd October the shape of an ace of clubs.[2] Mr. Maw perceived in the same object on 11th September delicate veins of comparative brightness, termed by him "submerged bridges."[3] Indeed he believes this to be a constant feature of large spots, the umbræ of which, viewed with a suitable eye-piece, appear no longer uniformly dark, but marked with fine traceries in chiaroscuro. These cannot at present be photographed, and their visual detection accentuates the indispensable co-operative functions of the eye and the sensitive plate.

The level of sun-spots has once more become a subject of active debate. Yet it was believed to have been determined once for all in the eighteenth century by the geometrical reasonings of Dr. Wilson. The characteristic perspective effects of depression below the surface were noted by him in a well-developed spot as it circuited the sun's globe in November 1769, and the saucer-like conformation of all such objects was universally admitted for a hundred years and upwards, notwithstanding frequent failures to verify the due optical consequences of their changing situations. At last, however, this "venerable theory" (as Professor Frost calls it) has been uprooted from the soil of conviction. It is denied by many on geometrical grounds alone; by some on physical grounds as well. Not that it has been finally discarded, but its credit is gravely impaired. Certainly *all* spots do not follow its prescriptions; probably very few strictly comply with them. Irregularities of form account for a good many of these deviations, but others cannot be so readily explained away.

[1] *Memoirs Brit. Astr. Ass.* vol. iv. p. 92.
[2] Maunder, *Observatory*, vol. xxi. p. 403.
[3] *Ibid.* p. 402, vol. xxiii. p. 283.

Mr. F. Howlett, in offering to the Royal Astronomical Society, 14th December 1894, three volumes of drawings representing the fruits of thirty-five years of solar scrutiny, declared uncompromisingly that the Wilsonian view must be abandoned.[1] Father Cortie's examination of them convinced him too that "the phenomena presented by many spots are directly contrary" to the current hypothesis, a mountainous rather than a cavernous structure being, in certain cases, indicated for the umbra.[2] Nor does the umbra usually vanish near the sun's edge, as it should if it were simply an excavation with sloping sides. It remains, on the contrary, persistently visible, although foreshortened into a black line. This, to be sure, might be a simple consequence of refraction by vapours congested within the cavity. The explanation is tempting, since it would avail to get rid of many anomalies; still it must not be adopted unreservedly. Originally suggested by Proctor,[3] it has been taken into fuller consideration by Mr. East[4] as a means of exit from the difficulties that hamper attempts to conceive rationally of the build of sun-spots.

There is, indeed, pressing need to conciliate opposing evidence. Thus M. Riccò,[5] at Catania, from eleven years' study of spots in their geometrical aspect, derived results strongly in favour of the Wilsonian hypothesis, computing for twenty-three especially symmetrical formations an average umbral depth of rather more than a thousand kilometers. Yet the discussion of the long series of Stonyhurst drawings led Father Sidgreaves[6] to ascribe to most spots a convex rather than a concave shape. Professor Hale[7] allowed small weight to testimony so contradictory as that regarding the apparent width of the penumbra at various distances from the sun's limb, but was inclined to consider the advocates of the Wilsonian doctrine as having rather the better of the argument. "In any case," he added, "they will hardly be ready to admit that the umbra is at a higher level than the penumbra, for it cannot be doubted that the penumbral filaments overlie the

[1] *Monthly Notices*, vol. lv. p. 73.
[2] *Ibid.* vol. lviii. p. 91.
[3] *Old and New Astronomy*, p. 382.
[4] *Knowledge*, vol. xxi. p. 89.
[5] *Astroph. Journ.* vol. vi. p. 91.
[6] *Monthly Notices*, vol. lv. p. 282.
[7] *Astroph. Journ.* vol. vi. p. 366.

umbra, and frequently unite to form bridges extending completely across it."

One of the most singular details of spot-phenomena is the occasional appearance of a large umbra as a notch on the limb. This implies its projection in a dark mass against the sky, the encroachment upon the bright disc being perhaps only an effect of irradiation. Its inconsistency with a depressed form was pointed out both by Mr. Howlett and by Father Sidgreaves.

Where, then, is truth to be found in this remarkable controversy? How can the jostling facts be reconciled? Compromises have been resorted to. Spots, it is averred, are cloud-like at certain stages of their growth, crateriform at others. Or individual spots belong to one or the other type, according to the circumstances of their origin. But these are subterfuges; let us take a broader view. The concavity, at any rate, of bridged spots is indisputable. The attribution to them of a "mountainous" character would throw the arrangement of their parts into utter confusion. Moreover, De la Rue obtained in 1861, by stereoscopic means, ocular proof of depression in one such object. The experiment might easily and usefully be renewed. A pair of photographs, taken at an interval of twenty-six minutes, gives, through the sun's rotation, just the right amount of difference in aspect for combination into one picture in relief. The moot question, "concave or convex," might thus receive a direct answer. Then if, in a long succession of instances, the answer preserved a uniform tenour, it might safely be concluded that anomalous appearances of lifted umbræ in spots seen obliquely are illusory and of purely optical production.

But we cannot even so escape from the entanglements of the subject. It has different bearings, which have all to be taken into account. Spots are very hot relatively to their light, and their thermal radiations are peculiarly conditioned. Professor Frost's determinations,[1] carried out at Potsdam in 1892, showed that absorption does not take increasing effect upon them with approach to the limb to anything like the extent that it does upon the corresponding radiations from the photosphere. "The reasonable inference

[1] *Astr. and Astrophysics*, vol. xi. p. 734; *Astroph. Journ.* vol. iv. p. 201. Cf. J. Halm, *Annals Edin. Observatory*, vol. i. p. 145.

from this," he wrote, "is that the spots are at a higher level than the photosphere, and hence less subject to the absorption of the sun's atmosphere." Mr. W. E. Wilson's[1] more delicate series of observations in 1893-4 showed likewise that "the radiation from the umbræ of spots does not suffer absorption when near the limb in the same manner as a point on the photosphere." Nevertheless Professor Langley[2] had found in 1874-5 "the decrement of heat in approaching the limb" to be very nearly in the same ratio for photosphere and spots. This flagrant contradiction between results equally authoritative may not be without meaning, since they were obtained at nearly opposite phases of solar activity: Langley's, three years after a maximum, when it was verging towards stagnation; Frost's and Wilson's, during a period of culminating disturbance. The two latter recommended systematic observations throughout an eleven-year cycle for the purpose of investigating the nature of the relationship, and they respectively threw out the alternative suggestions that, dur.ng its course, the thermal condition of spots, or the level at which they are formed, may undergo progressive changes.

A more promising explanation was offered by Egon von Oppolzer.[3] Spot-umbræ, he reminded perplexed solar physicists, are surmounted by abnormally hot chromospheric layers, certainly exempt from absorption. Hence the indiscriminate sum of their radiations and those of the underlying spots gains by comparison with those from the simple photosphere, at and near the marginal parts of the disc. Now the flame-stratum develops chiefly above spots of an active type; and spots of an active type predominate at epochs of maximum. This consideration at once removes the discrepancy between Langley's results on one side, and Frost's and Wilson's on the other. In the first series, absorption produced its full and due effects, because quiet spots being presumably in question, no appreciable overlying source of heat was present. In the second and third, the overlying source was so strong as in great measure to efface the gradations of heat-stoppage suffered by the object beneath. The disproportionate thermal

[1] *Monthly Notices*, vol. lv. p. 458. [2] *Ibid.* vol. xxxvii. p. 5.
[3] *Astr. and Astrophysics*, vol. xii. p. 739.

power of spots may be similarly accounted for. Our instruments measure, not only their direct radiations, but also those sent out by ignited materials, to some extent enveloping them.

The solar rotation is a subject much too important to be disposed of in a paragraph ; it need here only be said that a by-product of its detailed study has been to throw further doubt upon orthodox opinions as to the location of spots. The rates of axial movement deduced by Stratonoff and Wolfer from their progression round the sun appear, at least *primâ facie*, to compel the inference that they are veritably situated at a level higher than that of the photosphere.[1] Yet here again some fallacy is likely to be involved. In view of all these complications it is scarcely to be wondered at that the *Where?* has almost superseded the *What?* in recent discussions about solar maculæ. The upshot, so far, seems to be that they are essentially depressions, although depressions very shallow relatively to their superficial extent. Their abnormal geometrical behaviour is due, in part, as Mr. Maunder has suggested, to the cavities being *over-filled*, and the umbræ consequently dome-shaped;[2] in part to the optical elevation into view of bottoms which should, but for refractive action, be concealed by shelving sides. Their radiative irregularities, again, are explicable by the influence of their coronas of hot flames. As to their rotational anomalies, they must stand over for future consideration, with the remark that, to deduce the position of spots from the degree of their conformity to a supposed law of solar rotation, is to attempt the solution of one enigma by proposing another still more arduous.

The movements of sun-spots are of three kinds. There are first those that belong to them collectively, as objects attached to a rotating globe. With these we are not at present concerned. Next, they have individual "proper motions" of transport over that globe. Finally, they show internal movements variously connected with the processes of their development and decay. The last are mostly spiral or circular, and they evidently ensue upon inrushes of photospheric matter. They are sometimes performed round "black

[1] Frost, *Astroph. Journ.* vol. iv. p. 200.
[2] *Journ. Brit. Astr. Ass.* vol. vii. p. 121.

nuclei" as centres; and black nuclei are probably, as we have seen, interspaces between obscurely luminous umbral effusions. But the whirling of spots is not systematic or innate; it does not characterise them essentially; it occurs incidentally, and as a result of disturbance. No fixed rules prescribe its mode or direction. Opposite gyrations have been simultaneously observed in different members of the same group of umbræ, and even successively in a single spot. They are executed in other cases intermittently by fits and starts. A revolution is not often completed; the description of large angles is exceptional. Spots cannot then be described, in any true sense, as "solar cyclones"; the vorticose motions occasionally exhibited by them spring from temporary impulses, and cease when the force of these is exhausted.

The *proper* motions of spots are indicative of much more than has yet been learned from them. Three kinds of influence seem to be effective in producing them; namely, mutual action, action from without, and action from within. After segmentation, in the first place, umbræ repulse one another; they separate with great velocities. They behave like similarly electrified masses, but whether they really are such or not is an open question. In the second place, growing spots in general move rapidly forward. They share the common drift, but with an acceleration often amounting to three or four hundred miles an hour. It seems as if cooled materials, pouring down upon them from above, drove them forward with the added speed due to a wider circle of rotation. If this were actually the fact, however, macular increase and macular advance should always go together; and they are not uncommonly disunited. Processes of extension in spots may even be accompanied by retrogression over the sun's surface.[1] Indeed, the conduct of these strange objects is governed by no invariable rules. Strong tendencies visibly influence it; yet none that are irresistible. They can be annulled or reversed by countervailing circumstances. Hence the special need for guarded inferences in treating of this subject.

The movements of sun-spots in latitude are not visibly related to their drift in longitude. They are highly irregular, and not often conspicuous. Carrington, however, perceived in

[1] Maunder, *Knowledge*, vol. xvii. p. 198.

them a kind of inchoate method. Spots, according to his generalisation, situated within the solar tropics (so to speak) tend to approach the equator; spots outside the north and south limit of twenty degrees, to depart farther from it. But the exceptions observed are so numerous as sometimes to go near disproving the rule. We have said that spot-movements in longitude bear some marks of being communicated by exterior agencies. Those in latitude, on the contrary, suggest interior action. They are connected, most likely, with the hidden system of circulation prevailing in the body of the sun, and reflect its local perturbations.

A remarkable feature of photospheric commotions was referred to by Father Cortie at the meeting of the Royal Astronomical Society, 11th May 1900.[1] He termed it "alternation" in disturbance. A group of spots generally includes two chief members, posted respectively in the van and rear of the array. These *take it in turns* to develop. We are reminded of the reciprocal flickerings of the fragments of Biela's comet. Analogous pulsations, but on a larger scale, manifest themselves in responsive disturbances north and south of the solar equator. Mr. Maunder had already pointed out in 1894 that an "active train" of spots is often "accompanied by a feebler copy of itself a few degrees north or south. An outbreak of the first magnitude," he continued, "will indeed reproduce itself in several directions."[2] Somewhat similar correspondences are noticeable between volcanic foci on the earth; yet the inferences they suggest might prove misleading.

The occultation of a spot 107,500 miles across was observed during the solar eclipse of 15th March 1858. Its vast dimensions were, however, exceeded in the same year by those of an object with the "record" diameter of 143,500 miles. An enormous double spot, which appeared in June 1883, covered an area of 2500 million square miles; and the great spot of February 1892, with its dependants and outliers, spread still further afield. But such gigantic formations are rarely stable. Their history is one of tumults and vicissitudes. Comparatively small circular spots possess individually a much more lasting character, although great outbreaks are the longest lived in their successive modifications. The maximum

[1] *Observatory*, vol. xxiii. p. 230. [2] *Knowledge*, vol. xvii. p. 199.

duration so far registered was for a "composite disturbance," consisting of four very large spot-groups, and thirteen others of smaller dimensions, which appeared seriatim, and in obvious association, on a restricted region of the solar surface.[1] The manifestation continued for 527 days, from 25th September 1891 to 5th March 1893, while the sun completed nearly twenty-one rotations. About two rotation-periods represent, according to Father Cortie, the average life of a spot.

Most of what we know about sun-spots has been learned by a statistical method of inquiry. Nor can such methods be dispensed with in the future. But they do not alone suffice. They must be supplemented and reinforced by *individualisation*. Each notable spot should be studied in itself and in all its relations, singly, specifically, and generically. Efforts should be made to determine its nature, as though it were a solitary specimen. Can it, without doing violence to plain facts, be regarded as an excavation in the photosphere? Or, if apparent inconsistencies with this view be present, are they such as might be due to refraction? The hypothesis can only be tested by confronting it with particular cases, and trying definitely how far it avails to meet their exigencies. Refractive possibilities in the sun have been, until lately, almost ignored; they are now in some quarters vastly exaggerated. Still allowance has to be made for their realisation, in ways perhaps corroborative, rather than subversive of received theories.

There are many other doubts to be set at rest besides those regarding the interpretation of perspective effects. The record, indeed, of no significant structural detail should be omitted; and what detail of these enigmatical objects can be called insignificant? Above all, variations in their parts and features, whether simultaneous, successive, or alternative, claim the closest attention; since the establishment of a course of correlated changes comes very near to the detection of the underlying causal nexus.

The comparison of one spot with another is a natural sequel to the investigation of each spot in itself. Do their peculiarities, it may be asked, depend in any way upon heliographical position? Do they vary periodically? Can certain

[1] Cortie, *Observatory*, vol. xxiii. p. 280.

traits in sun-spots be classed together as inevitably associated, certain others as mutually exclusive? Wider questions, too, suggest themselves as to the place of spots in the general solar economy, and as to the nature of their connection with faculæ, prominences, coronal streamers, and the totality of solar phenomena. Attempts have been made, both by speculative and practical means, to throw light on these obscure topics, but with results not as yet wholly satisfactory. Meantime, additional facts are needed — facts systematically collected, methodically sifted and compared. Isolated observations are rarely of any considerable value in such complex matters. Meaning accrues to them just in proportion as they can be allied to others made in correspondence with them, but under modified conditions. "Correlate and compare" should be the watchword of astrophysicists.

# CHAPTER VIII.

## THE SPECTRUM OF SUN-SPOTS.

SUN-SPOTS give a remarkably compounded spectrum. It appears to sum up five different sets of effects. That is to say, the obscure longitudinal stripe corresponding to the umbra owns a quintuple origin. Each of its elements might be made the subject of a somewhat prolonged discussion. For the sake of clearness we will briefly enumerate them. They consist of: (1) A bright background of ordinary photospheric light; (2) a nearly continuous band of dense absorption, extending from the infra-red to the ultra-violet; (3) a select array of widened Fraunhofer lines; (4) nearly all the Fraunhofer-lines under a normal aspect; (5) a restricted number of bright lines.

Dunér of Upsala ascertained in 1891[1] that the *fundamental* radiance of spots is indistinguishable from that of the general surface of the sun. Their darkness is then due to increased absorption, not to diminished radiation. This fact decisively negatives some current theories, and thus limits the field of speculation as to the nature of spots. They are shown by it unmistakably to be regions where cooled materials of some kind accumulate. Of what kind those materials are, we can learn something—although not by any means all that could be wished—from their peculiar modes of arresting light.

A section of a spot-spectrum in the yellow-green is portrayed in Fig. 10 from a photograph by Professor Young. The belt of strong absorption which is its leading feature seems, but is not really, continuous. Young himself discovered in 1883 that it is made up of innumerable fine dark lines, set very closely together, or even actually overlapping. Each

[1] *Recherches sur la Rotation du Soleil*, p. 12.

individual in the multitude is, he tells us, "spindle-shaped—*i.e.* thicker in the middle where the spectrum is darkest—and tapers to a fine hair-like mark at each end; most of them can be traced across the penumbra-spectrum, and even out upon the general surface of the sun."[1] These observations, which require a high resolving power in the apparatus employed, were amply confirmed by Dunér. He perceived further that the lines are collected into groups, leaving chinks of undimmed photo-

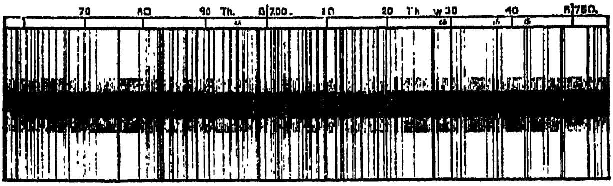


Fig. 10.—Portion of Sun-spot Spectrum, photographed by Professor Young in 1883. (From Young's *General Astronomy*. By permission of Messrs. Ginn and Co.)

spheric brilliancy between.[2] Within the limits of the "*b*-group" alone, no less than 300 of these dusky *fibres* were counted; above F, however, they become merged together by crowding, and below E by diffusion. Their separation and arrangement are most evident in quiescent round spots with intensely black nuclei—in spots, that is to say, commonly regarded as of the minimum type. Now such a spectrum as they constitute cannot be produced by liquid or solid matter, however minutely subdivided; it decisively claims a gaseous origin. Hence the darkening in spots is not merely an intensification of the "smoky" absorption veiling the entire disc; it is special and peculiar. So much can be safely asserted.

Perhaps the most distinctive part of the spot-spectrum is the collection, included in it, of accentuated Fraunhofer lines.[3] They are picked out to be widened and darkened on some recondite principle of selection, which varies from spot to spot, and from epoch to epoch. This was early noticed by Sir Norman Lockyer, and he pursued the inquiry with striking results. The discussion in 1886 of observations upon the spectra of seven hundred sun-spots, made at South Kensington

[1] Young, *The Sun*, p. 132. [2] *Astr. and Astrophysics*, vol. xi. p. 242.
[3] *Proc. Royal Society*, vol. xv. p. 257.

on a fixed plan during six years, led him to the following conclusions:—[1]

(1) "The most widened lines in sun-spots change with the sun-spot period."

(2) "At, and slightly after the minimum, the lines are chiefly known lines of the various metals."

(3) "At, and slightly after the maximum, the lines are chiefly of unknown origin."

In other words,[2] "As we pass from minimum to maximum, the lines of the chemical elements gradually disappear from among those widened, their places being taken by lines of which we have at present no terrestrial representatives." "Dissociation," in short, was the *mot de l'énigme.* As the sun's temperature increased with the growth of disturbance, substances in a terrestrial sense "elementary" were supposed to split up into exotic constituents, giving spectral lines strange to laboratory experience.

The evidence for the progressive change thus interpreted was indeed slight, except as regarded iron; and iron alone was taken account of in the confirmatory Stonyhurst observations. So far as they went, however, they were decisive, and all the more so that they covered a different spectral range (B to D) from that (D to F) examined at South Kensington. They showed demonstratively that, throughout the disturbed interval between January 1884 and October 1886, iron lines were all but completely replaced by "unknown lines" in the list of those affected in spots, while they duly reappeared upon the restoration of photospheric tranquillity. In connection with their behaviour, nevertheless, Father Cortie established an important distinction. Their presence or absence he found to be determined, not by the general flow of solar commotion, but by the nature of individual spots. In those of rent and ragged aspect and tumultuous proclivities, iron lines are ousted by unidentified faint rays; but in tranquil spots the iron spectrum is at all times prominent. And since the former sort prevail at maximum, the latter at minimum, the statistical outcome is that the spectral variations appear to depend simply upon the great cyclical pulsation of the solar globe. Only on special examin-

[1] *Chemistry of the Sun*, p. 324. [2] *Ibid.* p. 319.

ation they prove to be determined more locally and particularly than this would imply. In some unquiet spots, for instance, which developed near the minimum of 1889, the effacement of iron lines was as complete as if the epoch had been one of maximum. In fact (as the Stonyhurst astronomer remarked),[1] the widening of unknown lines is common to all stages of solar activity, provided spots of an appropriate character be at hand. This is not a distinction without a difference. It cuts the ground from under the assumption of periodical vicissitudes in the general chemistry of the sun. Iron is not everywhere, and inevitably reduced there to its elements as temperature and disturbance culminate together, but—if at all—only as a special effect in the hottest spot-craters. And this again brings up difficulties connected with relative temperature—difficulties which, in one form or another, perpetually recur in the study of astro-physics.

But there is more to be said. Further inquiries have materially altered the aspect of the case, for they have led to the transference from the "unknown" to the "known" class of so many spot-lines that the completion of the process may be confidently anticipated. Rowland's photographic comparisons have contributed most effectually to its advance. Young and Cortie have traced a crowd of sun-spot rays to vanadium; titanium claims as many, or more; and others perhaps originate from allied "rare" metals. This singular line of identification is very strongly traced. Thus *all* the vanadium lines, twenty-eight in number, between C and D are by turns broadened in spot spectra, although of evanescent faintness in the photosphere; nor does the conjecture seem unwarranted that the high temperature compounds with nitrogen and oxygen, both of this metal and titanium, may yet be recognised in umbral chemistry. The distension in a spot of two vanadium lines, at $\lambda$ 5728 and $\lambda$ 5731 respectively, is well shown in Fig. 10. They are of quite minor importance in the Fraunhofer spectrum.

Father Cortie surmises that the vapours absorbing in spots may be associated by their approximate conformity to a certain standard of density. "The level of sun-spots," he

[1] *Memoirs Royal Astr. Society*, vol. l. p. 50.

suggests, "is possibly the level of the faint lines of such metals as have an atomic weight about 50."[1] Iron, nickel, titanium, and vanadium, all assiduous frequenters of umbral cavities, belong to this category. But the rule is compromised by exceptions and incongruities.

The actual state of the case is this. There is no evidence of elemental dissociation in sun-spots, but spectral diversities are obvious and persistent. They indicate the disappearance of iron from tumultuous formations, and the emergence in them of titanium and vanadium. There are doubtless concomitant changes, but they await ascertainment and particularisation. A *caveat*, however, has to be entered. The principle upon which these inquiries have been conducted is imperfectly assured. It is commonly taken for granted that the widened lines constitute the spot-spectra; that they, and they alone, represent the emanations of the constipated vapours blotching the lustrous disc. But this is a somewhat arbitrary assumption. The theory of line-expansion by pressure is very imperfectly understood. The phenomenon does not occur uniformly and invariably. Lines of different substances are differently affected by it; lines even of the same substance are unlike in their susceptibility to its influence. The inferential building up then, of spot-spectra out of widened lines is subject to many qualifications. These do not lessen the importance of the observed relation, but they importantly modify it.

The iron lines intensified in spots, presumably by the specific action of their nuclear vapours, are often unsymmetrically broadened. They are usually diffuse towards the violet side, sharp to the red. This may point to the presence of chemical compounds;[2] since the flame-spectra of metals and of their oxides seem to be differentiated just by the development, in the latter, of these peculiar shadings. The possibility must accordingly be admitted that iron-oxides exist in the sun. Yet the implied temperature is improbably low, since they can be broken up here on the earth by the simplest metallurgical processes. But they might perhaps form

[1] *Monthly Notices*, vol. lviii. p. 373.

[2] Frost-Scheiner, *Astronomical Spectroscopy*, p. 177; J. S. Ames, *Astroph. Journ.* vol. i. p. 89; Hartley, *Proc. Royal Society*, vol. lvi. p. 192.

transiently (so to speak) in spots, as a result of the local chilling of swiftly circulating material. It may be added that the iron lines distinctive of spot-spectra are so-called "low-temperature lines." They are brilliant in the electric arc, but tend to be outshone by others in the higher excitement of the spark.

Further complexity was imparted to spot-absorption by the appearance of certain dusky bands, of which nine, situated below D, were observed early in 1885 at Stonyhurst,[1] and no fewer than seventeen more refrangible in 1880-3 at Greenwich. One proved identical with a fluting drawn by Young in 1872,[2] and all were resolvable into densely packed lines. Nothing is known, or can even be conjectured, as to their origin; but they are clearly symptoms of disturbance, since, with the sudden advent of a solar calm in October 1886, they at once utterly vanished.

Mr. Evershed considers the majority of the unaffected Fraunhofer lines in spot-spectra to be possibly spurious;[3] they may, he thinks, be inherent, not in umbral light, but in the photospheric glare diffused equally over spots and the surrounding sky. Some of the ordinary dark solar lines, however, thin out in crossing umbræ, and a few show traces of partial brightening. Moreover, the radiations from spots cannot escape transmission through the reversing layer, and are hence subject to precisely the same absorption exerted upon sunlight in general, so that the Fraunhofer spectrum in its integrity truly belongs to spots, notwithstanding the reinforcement of some of its components and the enfeeblement of others through influences special to them.

One of the most remarkable features of spot-absorption has still to be noticed. Helium, as we have seen, makes no show in the Fraunhofer spectrum. Yet a helium-envelope surrounds the sun to a depth of five thousand miles. Every ray of sunshine sent abroad into space has been sifted through this huge volume of gas, which, by its anomalous inertness, bids defiance to "Kirchhoff's law." Emitting complex ranges of vibrations, it nevertheless exacts no corresponding toll of absorption. Its transparency seems absolute. Either it is so

[1] *Monthly Notices*, vol. xlvii. p. 19. [2] *Nature*, 12th Dec. 1872.
[3] *Astroph. Journ.* vol. v. p. 248.

hot that it replaces the light arrested, or its arresting power is nullified by rarefaction. The former alternative is excluded by the consideration that an excess of temperature should be notified by the presence of bright helium lines in the general spectrum of the sun, and they are no more visible in it than dark ones. Hence the absorptive incapacity of chromospheric helium may provisionally be attributed to extreme attenuation.[1] This view has gained plausibility through the discovery that helium in or near spots acts at times normally upon light, for the vapours and gases producing umbral obscurity are assuredly, on any theory of spot-formation, denser within than outside the apparent cavity. The shading then at $D_3$, like the fusiform shape of the sodium pair below it (see Fig. 11), results from increased pressure. It is usually significant of vehement disturbance. In twenty or thirty spots with flaming appendages — and mostly in their penumbral regions—Professor Young has seen the yellow helium ray reversed;[2] it was similarly visible to Professor Naegamvala in the huge vortex of February 1892,[3] and to Mr. A. A. Buss of Manchester, on 17th March 1899,[4] in a spot the incessant activity of which was the more remarkable on account of its occurrence near an imminent minimum. Absorption by the deep red helium ray at λ 6678 was three times observed in spot-spectra by Father Perry during 1883,[5] but its chemical meaning was then unsuspected. Now that the helium-spectrum has been unravelled, further particulars might easily be learned as to the associates of $D_3$ in spots. Its isolated occurrence is improbable.

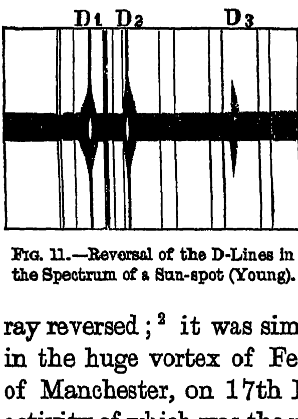


FIG. 11.—Reversal of the D-Lines in the Spectrum of a Sun-spot (Young).

Spot-spectra are crowned and completed by the frequent superposition upon them of vivid rays. These originate from the gaseous effusions often accompanying the formation

[1] Gases glowing electrically in vacuum tubes were found by M. Cantor incapable of absorption. But the results of further experiments must be awaited before conclusions in so delicate a matter can be availed of to elucidate the state of helium in the sun.

[2] *Nature*, 12th Sept. 1895; *The Sun*, p. 134.

[3] *Monthly Notices*, vol. lii. p. 424.

[4] *Journ. Brit. Astr. Ass.* vol. ix. p. 253.

[5] *Ibid.* vol. vii. p. 191.

and transformation of spots. They are readily identifiable. Hydrogen lines and the H and K of calcium are the most frequently brightened; $D_3$ is sometimes bright over the umbra, dark in the penumbra, of the same spot; and "double reversals" of the sodium "D pair" are quite commonly observed. The phenomenon is illustrated in Fig. 11. The brilliant ray shining at the core of the fuzzy spindle, into which each of the coupled lines is broadened, evidently proceeds from an overlying hotter and rarer stratum of sodium-vapour. The magnesium group "*b*" is occasionally affected in the same way. The "rosy veils" in spot umbræ give out, as might be expected, hydrogen rays, and "bridges" are also loci of emission. The ultra violet members of the hydrogen series are never present, bright or dark, in spots; and the fifth line ($H\epsilon$), which falls just within the region of visibility, has often been looked for in vain. In some of Professor Hale's spectrographs, however, of the giant spot of February 1892 it showed faintly bright beside the more conspicuous H of calcium.[1] So far the record stands alone. It has a particular interest from the ambiguous position occupied by this ray in the solar spectrum.

The agitation prevailing in spots is often betrayed by line-distortions, telling of the swift recession or approach of vapours congregated in them. The condition of the C-line, as sketched by Professor Hale, 13th February 1892, in the same spot, is shown in Plate VI., Fig. 2. The brilliant patch over the umbra is of normal wave-length; it was derived from a flame radially immobile; but the hook-like appurtenance of the dark line testifies to an extraordinary outrush of cooler gas from the lower part of the formation. We can, to a certain extent, trace its course. It started outward with a uniform velocity away from the earth of about 120 miles a second. This slackened unequally, as can be seen by the breadth of the "hook" at its junction with the line; and the whole mass of hydrogen came to rest at a distance of thirty to forty thousand miles from the point of issue, which (it is worth noting) was at the very middle of the nucleus. The nature of the force raising this brief but tremendous storm cannot readily be imagined. Its abrupt

[1] *Astr. and Astrophysics*, vol. xi. p. 313.

development marked an acute crisis of disturbance, to which the earth responded with magnetic twitches and auroral illuminations.

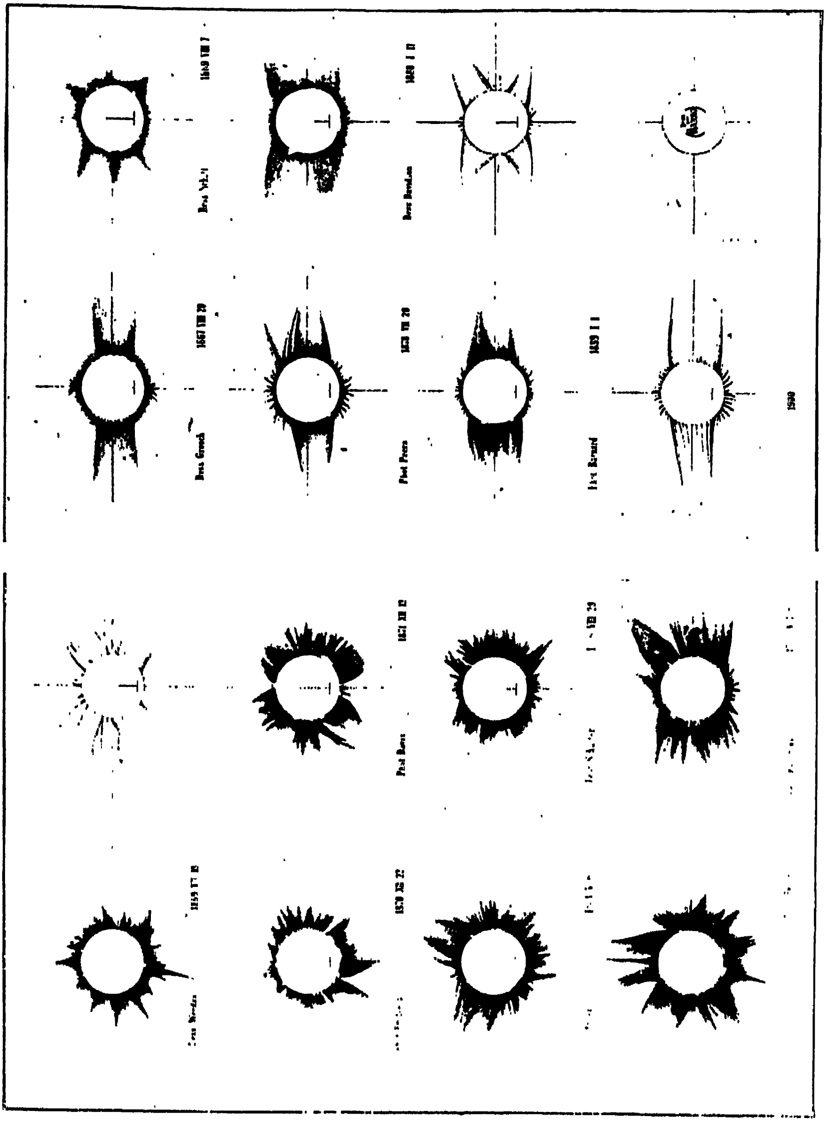
Motions in spots seem to be limited and local. They can be inferred to prevail with great violence at certain levels, while complete tranquillity reigns at others. This, at least, is the only explanation of the chemical peculiarities of solar hurricanes. Nothing, for instance, is commoner than the raging of hydrogen-storms amid profound calcium-calms. Nay, lines belonging to the same substance may indicate for it simultaneously rest and motion. Thus a few iron lines are at times observed to be displaced or twisted through the effects of rapid approach or recession, while the remainder maintain their usual positions and aspect. The anomaly is most striking, and challenges persistent attention. Sir Norman Lockyer meets it with the dissociation-hypothesis; but this raises more difficulties than it removes.

Enough has been said to show that numerous and most curious problems await solution by students of sun-spot spectra. The subject is wide enough to occupy a band of specialists, and its remoter implications can still be only surmised. Nevertheless, definite conclusions are not wholly out of reach. First, as to the cause of nuclear darkness. It is certainly to be found in augmented, and (so to speak) reiterated absorption. Spots are not simply rents in a shining veil, exposing an obscure substratum. They are not super-heated regions, where processes of condensation are suspended. The photosphere is screened, not perforated, by them. Moreover, the screening is by interposed vapours. Umbral absorption is mainly, if not altogether, of the gaseous kind. It is essentially linear and banded. No part of it can be safely attributed to the action of a foggy precipitate such as modifies elsewhere the "surpassing glory" of the disc. They probably differ in this respect from "pores" and "veiled spots," but specific inquiries on the point have yet to be made.

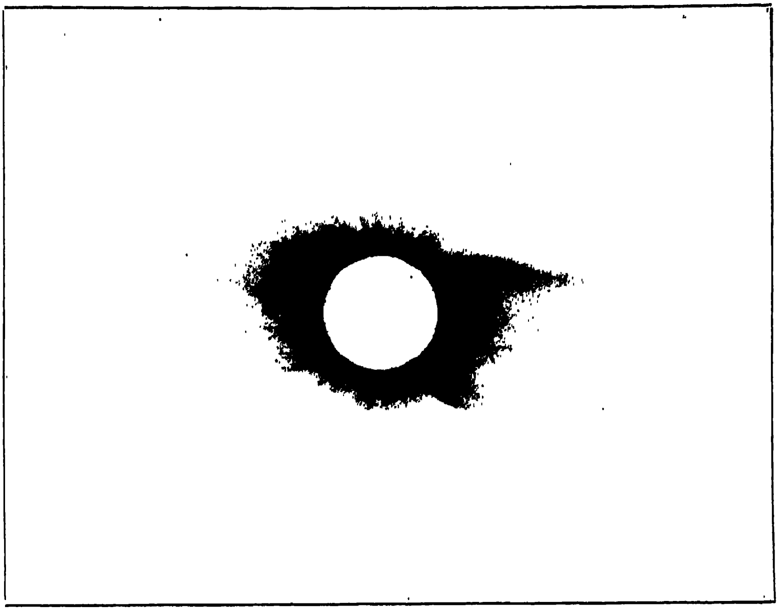
There are strong indications that spot-spectra originate under conditions of increased pressure and diminished temperature. Still the coolest umbræ must be hotter than the reversing layer, for otherwise the Fraunhofer lines would show bright against them, and, as we know, they cross

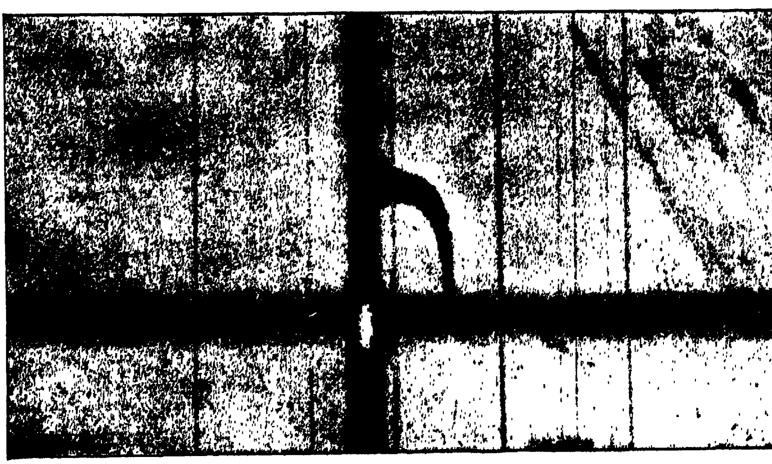
for colour often show signs of having progressed further on

PLATE V.



Types of the Corona 1860-96, with an Anticipatory Sketch of the Corona of 1900. Drawn by M. Hansky. (From the *Observatory*, February 1898.)

1. 

2. 

1. The Corona of 1900. Drawn from Photographs by L. E. Jewell.
2. Reversal and Distortion of the C-Line in Sun-spot (Hale).

them in dusky array. This circumstance is fundamental in solar thermal relations, yet has been generally overlooked. The ordering aright of such relations is a prime desideratum in solar physics, and should serve as an indispensable guide to the interpretation of spectral diversities.

# CHAPTER IX.

## FACULÆ AND PROMINENCES.

FACULÆ are outgrowths from the photosphere. This is known by direct observation. They have been seen and photographed jutting from the limb as rotation brought them into, or carried them out of view. It is also inferred from their superior brilliancy, which might serve to measure the opacity of the veil spread over the surface they surmount. On the other hand, they escape none of the Fraunhofer absorption; the whole range of solar dark lines is invariably present in their analysed light. Hence their position can be defined as intermediate between the "smoke veil" and the reversing layer. This consideration affords a safe holding-ground for reasonings about the status of these remarkable objects. They testify to internal commotions of the same nature as those giving rise to spots, but exempt from their heliographic limitations. Faculæ are not confined to the spot-zones; they develop all over the solar globe. Since, however, spots invariably claim their attendance, they are most numerous in the latitudes frequented by such disturbances, while showing independent maxima much nearer to the poles.[1] But their imperfect visibility upon the disc greatly restricted their observation, until Professor Hale and M. Deslandres almost simultaneously invented a method for spectrographically recording them.[2]

It depends essentially upon the use of a double slit—Janssen's valuable invention for isolating spectral rays. Celestial objects can in this way be photographed in mono-

[1] Mascari, *Astroph. Journ.* vol. vi. p. 372.

[2] *Astr. and Astrophysics*, vol. xi. pp. 159, 414.

chromatic light—that is to say, their forms in each separate chemical element can be distinctively recorded. The importance of the fresh start thus made is difficult to exaggerate. With a double slit and a sensitive plate, the comparative distribution of glowing vapours in the sun can be satisfactorily investigated, and anomalies connected with their distribution, if not removed, at least fully recognised and defined. All spectral rays, nevertheless, are not equally available for all purposes. In chromospheric photography, for instance, the calcium H and K offer immense advantages, not only because of their actinic efficiency, but still more on account of the broad bands of shadow rendering them conspicuous as Fraunhofer lines. These serve to protect against atmospheric glare the bright lines superposed upon them at the edge of the sun; and glare is the worst foe of daylight photography. In systematic work, moreover, K is, for more than one reason, always preferred to H. And so came to be established, in two continents at once, a new branch of astronomical art—the art of picturing the sun and its surroundings in calcium-light of a single quality.

The first and immediate object in view was the day-by-day photography of prominences; but it was very soon found practicable to extend the work from the limb to the disc. One slit was caused to travel across the sun's image, which had a diameter of two inches in the Chicago twelve-inch refractor, while the motion of the second was adjusted so that it exactly kept pace with the K-line, admitting it alone, through a chink just two thousandths of an inch in width, to impress the sensitive plate. At Chicago, the first experiment of the kind was made 28th December 1891, and a similar mode of procedure was described by M. Deslandres before the Paris Academy of Sciences, 8th February 1892.[1] The upshot in each case was the discovery that K is doubly reversed over extensive tracts of the photosphere. Plate IV., Fig. 1, shows the sun self-portrayed in calcium light, 11th April 1894. The lines crossing the photograph are accidental imperfections, one set originating from dust-particles in the jaws of the slit, the other from irregularities in the movement of the siderostat. The regions of reversal are not confined to the neighbourhood of spots, but spread irregularly over the sun's surface. The

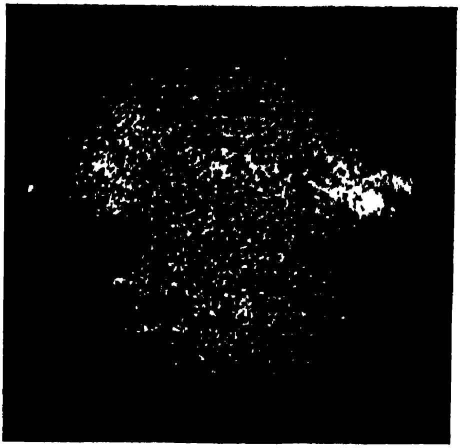
[1] *Comptes Rendus*, 8th Feb. 1892; *Knowledge*, vol. xvi. p. 230.

individual bright forms they include are often bent into spirals or doubly curved. They correspond very closely, both in aspect and position, with faculæ directly seen, and were at once, by Professor Hale, identified with them. M. Deslandres, however, classing them as a species of hybrid between faculæ and prominences, bestowed upon them the compound name, expressive of this mixed quality, of "facular flames."[1] Hale's view, in other words, was that the novelty disclosed by his "spectroheliograph" consisted in the emission by faculæ of bright "H and K" by way of supplement to their regular photospheric spectrum, while Deslandres considered that the new investigation applied to a distinct kind of objects, neither prominences nor faculæ, although partaking of the nature of both. The question raised is difficult; let us briefly examine its bearings.

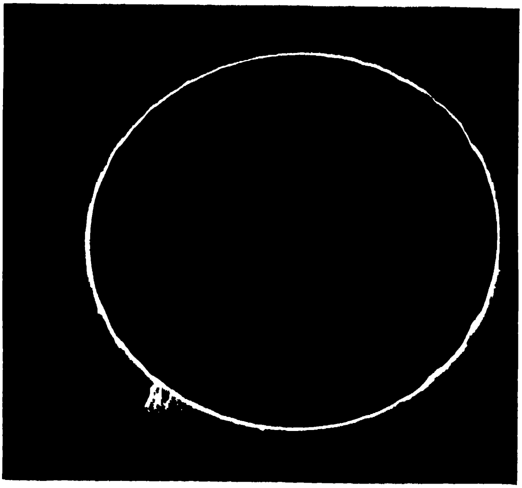
The calcium-flames photographed at Paris and Chicago are certainly not prominences. Their positions do not coincide with those of the chromospheric offshoots. They appear where prominences are not, and *vice versâ*. Nor are prominences bright enough—unless by a rare exception—to show in relief against the sun; they are strictly objects for marginal spectroscopic study. Finally, motion-displacements are conspicuous in them, and are absent from the sinuous shapes on the disc. The objections to identifying these with faculæ are less obvious, yet seem equally insuperable.

Faculæ belong no less unmistakably to the photosphere than the Himalayas do to the earth's crust. They are flung upward from it; they subside back into it. Their light is of the same brilliantly continuous quality; it is marked by the same kind and amount of linear absorption. It has then been sifted through all the vaporous strata amassed above the surface of the sun. This gives the key to the position; for it compels the inference that while faculæ are situated beneath the reversing layer, the allied gaseous forms must be located above it. The argument for their comparative elevation is cogent. The reversing layer, as we know, is rich in calcium vapour cooler than the photosphere, and, *à fortiori*, cooler than the flames detached by their superior lustre from the photosphere. Their calcium-rays should, accordingly, be effectually

[1] Deslandres, *L'Astronomie*, Dec. 1894.



1.



2.

1. The Sun portrayed in Calcium Light. From a Photograph by M. Deslandres.
2. Photograph of the Chromosphere and Prominences taken by M. Deslandres at 5 h. 40 m. P.M., 31st May 1894.

stopped by the reversing layer; they could not by any possibility be transmitted through it. Hence the bright "K" in which the solar disc can be depicted must originate above the region where Fraunhofer absorption takes place. The wreathing forms emitting it belong to a different locality from that of true faculæ. They are chromospheric, not photospheric, developments. Yet, as just stated, they cannot be assimilated to prominences. They probably lie at the base of the chromosphere, and they follow the distribution of faculæ with close, though not rigid exactitude. Hydrogen is at times represented in their spectra by a crimson glimmer of C, so they are not composed of calcium solely; but their real nature and place in the sun's economy remain admittedly enigmatical. We are only sure that they spring up in close relation with faculæ as symptoms of the same disturbances. That their relation to them is one of actual identity seemed indeed at first sight scarcely open to doubt; yet for the reasons just assigned they must be regarded as separate phenomena.

The connection of faculæ with spots is not, as we have seen, of the "mutual" kind. Their reciprocity—as a typical Irishman might say—is one-sided. Outside the spot-zones, where solar commotions have a less vehement character than nearer to the equator, faculæ lie "extended many a rood" in sluggish inactivity during intervals long enough for the working out of manifold changes in the brilliant circumvallations of spots. These are very often crowned with prominences, which, however, develop somewhat tardily. Nascent umbræ are rarely accompanied by them, while moribund umbræ offer a favoured site for their growth. Thus a remarkably brilliant prominence, agitated by violent motion, towered above the eastern limb as it was passed, on 3rd March 1892, by the shrunken remnant of the vast spot-group which had slipped out of sight round the western limb a fortnight previously.[1]

Prominences are related to the chromosphere in very much the same way that faculæ are related to the photosphere. They arise from it by effluence or eruption. Now

[1] Deslandres, *Comptes Rendus*, t. cxiv. No. ii.; *Journ. Brit. Astr. Ass.* vol. ii. p. 237.

the chromosphere itself has a markedly eruptive aspect. It presents no billowy ocean surface, but resembles rather a Tartarean meadow planted with stalks and grass blades of fire, waving under some unimaginable furnace-blast. With clear definition, a filiform texture is everywhere apparent. The "straw-thatch" effect of penumbræ denotes a similar peculiarity in photospheric materials, and that it is shared by prominences can be inferred from their frequent construction, as if out of the untwisted strands of a rope.[1] The red rim of the eclipsed sun is conspicuously jagged, and its saw-like outline suggested the name *Sierra*, originally bestowed upon it by Airy in 1851. It does not, then, represent a fluid envelope in a state of equilibrium. There is another reason why this is impossible. The chromosphere does not preserve a uniform depth. Averaging about 5000 miles, it is subject to irregular and temporary variations, as yet imperfectly observed and entirely unexplained. General subsidences are even affirmed to take place. One such was noted with surprise by Trouvelot, June to August 1875.[2] He had frequently observed extensive local depressions, but never before a universal shoaling. He attributed to the sharper views of the photosphere afforded by this removal of part of the interposed medium, his discovery of "veiled spots," imperfect umbral formations, owing their abortive character, perhaps, to their unfavourable situation near the poles. In 1887, the height of the chromosphere, measured thirty-two times by Dr. Fényi, S.J.,[3] was found to diminish above the spot-zones, and sensibly to increase outside their limits. It would be of interest to determine whether this condition prevails commonly, or whether it is restricted to epochs of minimum.

Prominences are of two varieties—eruptive and quiescent. These differ chemically, visually, and heliographically. Eruptive prominences are of a more mixed constitution than the quiescent sort; they include many more ingredients; they give an intense carmine light, have jet-like or upspringing shapes, and are mostly confined to the spot-zones. They are genuine fire-fountains, while quiescent prominences frequently

[1] Evershed, *Astr. and Astrophysics*, vol. xi. p. 240.
[2] *Amer. Journ. of Science*, vol. xi. p. 169 (1876).
[3] *Publicat. Haynald Observatory*, Bd. vi. p. 40.

resemble cloud-banks. The former are individual outbreaks; the latter unite into communities, counterfeiting banyan groves, ranges of jungle, fields of cirrus. Usually connected with the chromosphere by stems or trunks, they in some cases, not only float free in isolated masses, but, still more remarkably, are generated at great elevations above it, as if by the spontaneous illumination of pre-existing material. The analogy with terrestrial condensations in an azure sky is obvious, but may be quite misleading.

Quiescent prominences develop on an enormous scale, nor always tranquilly. Formations, at least, which are in some respects cognate with them, become, on occasions, the scenes of striking explosive accidents. So that their generic title must be understood in a restricted sense. Thus the cloud-like character of a huge object photographed by Deslandres,[1] 31st May 1894, seemed vouched for by its vicinity to the south pole, and by the large extent of the solar limb garnished by it. At 2 P.M., when it was first pictured—as usual, in calcium light—its height, apart from foreshortening, was $2' 20''$, or 63,000 English miles. At $4^h 27^m$ it had sprung up to 135,000, and $73^m$ later still to 270,000 miles (see Plate IV., Fig. 2), an elevation far beyond any recorded for objects of the kind situated more than sixty-five degrees from the solar equator, while this wonderful structure spread from the seventieth to the eighty-first southern parallel. Perceptibly filamentous, it seemed to grow by the elongation of its component threads or ribands, and included within its vast bulk probably the minimum conceivable quantity of matter. On the same plates, a group of smaller but intensely active prominences registered themselves at the solar antipodes.

An example of a transient apparition, difficult to classify, is given in Fig. 12. It simulates a portentous conflagration. From bottom to summit the red pillar of hydrogen measured 166,000 miles, according to Dr. Fényi's observation at $2^h 20^m$, 19th September 1893. But it wholly lacked any interior principle of stability. Opposite, and excessively swift movements in line of sight of the base and shaft betrayed the progress of destructive change. The catastrophe was not long delayed. Within less than half an hour all was over. A

[1] *Comptes Rendus*, 25th Jan. 1897.


Fig. 12.—Prominence observed at the Haynald Observatory, 19th Sept. 1893.
The spectroscopic line-displacements due to motion are illustrated in the upper sections of the figure.

rush upward set in at the rate of 132 miles a second, carrying the frail edifice to a height of 224,000 miles. A minute and a half later, it had faded and dissolved, "like the baseless fabric of a vision," leaving just "a rack behind" in the shape of an insignificant protuberance hedged in with faculæ. "Throughout the course of its appearance," Dr. Fényi wrote,[1] "the entire object consisted simply of very bright luminous bands or strips scattered one after another in ragged forms, and apparently lying nearly at right angles to the limb of the sun. They were strikingly bright even in the highest parts of the prominence. The form as a whole was also like a band or stripe, which had no pronounced inclination, but stood erect nearly in the direction of the sun's radius."

This amazing outburst was repeated with enhancements, nineteen hours later, at a point on the sun's limb almost diametrically opposite to its predecessor. The height in this case attained was 300,000 miles, the mean velocity of ascent being 214 miles a second, besides which, retreat from the earth was indicated for the entire mass at the rate of close upon 160 miles a second. A convulsion at least equally violent was witnessed by the same observer on 24th December 1894,[2] when a brilliant and wide-spreading, yet tolerably tranquil prominence, 56,000 miles high, suddenly began to mount, and attained in thirty-five minutes the towering stature of 300,000 miles. Speedy disorganisation ensued. Less than two hours after the explosion its scene was vacant. The body affected by it had been shattered out of existence by its destructive violence.

The Kalocsa observations were made with a visual spectroscope. Simultaneous photographs would have been of especial value for comparison with them, but leisure was not afforded for combining methods. The three objects they referred to were palpably identical in character. All showed precisely the same kind of structure. They were made up of glowing vertical bands, collected into loose sheaves, or scattered in outlying detachments. Each enormous aggregation, too, stood erect during the tumultuous processes of expansion and collapse. They were related to spot-groups, if at all, only

[1] *Astr. and Astrophysics*, vol. xiii. p. 124.
[2] *Astroph. Journ.* vol. i. p. 212.

by *diametrical opposition.* The singular counterbalancing tendency of solar disturbances is frequently conspicuous, and perhaps rarely or never absent. Two gigantic, although ephemeral apparitions, thus coupled, were, for instance, observed by Trouvelot, 26th June 1885;[1] and on 16th August of the same year he noted the apparent connection of a prodigious chromospheric outburst with a spotted condition of the limb 180° distant. A relief of pressure may be concerned in these phenomena, as in volcanic eruptions; if so, the lift, or diminution of gravity, must act right across the solar globe, quickening convection-currents and facilitating the antipodal delivery of extra supplies of heat. In point of fact, the usual premonitory symptom of the explosive development of prominences is a disengagement of light.[2] Exceptional brilliancy is the forerunner of abnormal activity. No satisfactory cause, however, can be assigned for the imagined relief of pressure, since tidal influences are fairly out of the question. Only one undeniable inference can be derived from the contrary symmetry of solar commotions. It is that they are extremely deep-seated. They have their roots in the hidden profundities of the great globe they agitate exteriorly. They are not then mere local accidents; they make an intimate part of the solar economy. The recognition of this characteristic is interesting and important.

The tallest prominences are ordinarily the least coherent in structure. An example is shown in Fig. 13, from a drawing made by M. Fényi, 3rd October 1892. The object it portrays was almost unique in its fantastic and colossal form. Overarching thirty degrees of the limb, it rose above it to a height of nearly a quarter of a million of miles. Its fragmentary composition was patent.[3] Under the eyes of the delineating artist it was "in the act of being blown to shreds." Photographs happily secured at Chicago seven hours later, exhibited it as then fallen to less than one-quarter of its high estate, while of augmented lateral spread. These represented, of course, its calcium aspect, the Kalocsa drawing its shape in red hydrogen; but there was no evidence of the two

[1] *Comptes Rendus*, t. ci. pp. 50, 475.
[2] Trouvelot, *Bull. Astr.* t. iii. p. 21.
[3] Fényi, *Astr. and Astrophysics*, vol. xii. p. 38.

vapours being differently distributed throughout this bubble edifice. Facular patches marked, on the sensitive plates, the points both of rise and re-descent of the materials constituting it. Next morning only some insignificant wreckage strewed its place; virtual annihilation had overtaken it.

FIG. 18.—Prominence observed at the Haynald Observatory, 3rd October 1892. Height, 8′ 51″.

The tremendous velocities observed in prominences constitute a formidable problem in solar physics. They not infrequently exceed the critical rate of 383 miles per second; that is to say, they transcend the limit of the sun's gravitational controlling power, and, apart from possible resistance by a medium, should carry the substances animated by them finally away into space. The shapes and motions of pro-

minences, however, clearly indicate some retardative action,[1] although its excessive feebleness, at least in coronal regions, can be inferred from the unimpeded circulation of comets passing within a hundred thousand miles of the sun's surface. Hence it is only a surmise, not a certainty, that chromospheric outbursts are attended by irrevocable loss of matter. The swiftest so far recorded took place, 17th June 1891, in connection with a spot just disappearing through rotation. A concentration of vivid luminosity gave the signal that something unusual was impending, "and after six P.M., Kalocsa mean time," M. Fényi wrote,[2] "the point at 281° shone with so great a brilliancy that its reddish light seemed to become white; an enormous displacement of the spectrum towards the blue, at a medium height above the sun's limb, indicated at the same time an approach of the hydrogen in our direction with a prodigious velocity." The entire object, which was composed of glowing filaments, lay, in fact, on the more refrangible side of the C-line, as the result of approaching speed up to 550 miles a second. A vertical ascent at the rate of 300 miles being meanwhile directly visible, a total velocity (neglecting an uncertain third component) of about 680 miles a second must have been attained in this amazing explosion. Trouvelot's observation a few hours earlier of a brilliant and peculiar facular blaze at the place where it occurred[3] was significant of the intense energy pent up in the spot-group, waiting release by the figurative trigger-touch.

This prominence easily wins the prize for rapidity of movement; yet the competition has been keen. Velocities of the same order, arising under similar circumstances, have been frequently determined. They appear, indeed, improbable, and have been stigmatised as "fabulous." No actual transport of matter, it is alleged, can be in question, but merely a swift transference, through gases previously obscure, of a luminous condition.[4] But this does not account for the conspicuous shiftings of spectral lines, which could not ensue from the progress of incandescence through stationary matter. They

[1] Deslandres, indeed, observed velocities to become, as a rule, accelerated in the upper sections of prominences (*Éclipse du 16 Avril*, 1893, p. 60); but this need not imply that they spring up in a perfect vacuum.

[2] *Astr. and Astrophysics*, vol. xi. p. 63.

[3] H. H. Turner, *ibid*. p. 67.

[4] Brester, *Théorie du Soleil*, p. 54.

demand the strict application of Doppler's principle; real velocities must correspond to them. Nor, even if there could be deception about the movements of prominences *in* the line of sight, is illusion possible about those *across* it. And both kinds are of the same order of speed; they are complementary; they represent different aspects of identical disturbances. This is not all. Prominences are often visibly twisted; they are composed of spirally mounting flames; while to this helical conformation correspond gyratory movements, at times disclosed by the spectroscope. Here, at any rate, we have to do with bodily transportations of matter; "luminescence" cannot be propagated vortically. Besides, the measured speeds are as difficult to explain on one hypothesis as on the other. Chemical action does not spread instantaneously. Through the tenuous gases of the chromosphere, a maximum rate of one mile a second might be assigned to its progress—a rate, that is to say, some hundreds of times slower than the velocities to be explained. That they are somehow of electrical production is a safe assertion, likely to be true, if not in an immediate, then in a remote sense. Yet we are little the wiser for the admission. The "floating of an idea" in the mind does not constitute knowledge; and a speculation is only valuable when it offers a definite starting-point for practical research.

Total eclipses have ceased to be indispensable for the prosecution of chromospheric studies. Day by day the red rim of the sun, with the strange forms protruding from it, can be viewed spectroscopically; and day by day the same objects vestured in violet can be photographed under the broad shelter of the Fraunhofer K-line. Nevertheless, noontide darkness, when it comes, brings very appreciable help. Differences are noticeable between what can be seen in and out of eclipse. According to the late Professor Tacchini,[1] the chromosphere always appears deeper under cover of the interposing moon, because it is surmounted by a pink-white margin, giving continuous light, and therefore spectroscopically invisible in daylight. Some prominences are probably of analogous composition. Only their skeleton-forms come out in the crimson radiance of hydrogen; they are compacted and clothed with white

[1] Hale, *Astroph. Journ.* vol. iii. p. 377.

materials, the shining of which is effaced by the glare of common day. A spectroscopic survey of the chromosphere and its appendages should hence always be made immediately before and after every eclipse, for comparison with the direct photographic records obtained during the corresponding totalities. For the present the information acquired by daylight work at the edge of the sun remains under a partial slur of incompleteness.

The objects called "white prominences" belong indeed wholly to the pageantry of eclipses. First noticed by Tacchini at Caroline Island, 6th May 1883, they showed as lucid jets about a hundred thousand miles high, with a surface like granulated silver. Attempts made, after the return of daylight, to view them prismatically proved fruitless; they gave forth no hydrogen or helium rays. Again at Grenada, 29th August 1886, a gigantic helical structure, described by Mr. Maunder as "of the intensest silver whiteness,"[1] towered three hundred thousand miles above the limb of the moon. Its spectrum, photographed by W. H. Pickering, included bright H and K, and Professor Hale accordingly entertained the hope that such objects might come within the range of his spectroheliograph; but so far no trace of them has been caught outside total eclipses.

Dark chromospheric forms are not unknown. A "black protuberance," observed by Trouvelot at Meudon, 7th October 1892,[2] might have been only a negative impression, like "black" flashes of lightning; yet it in a measure falls into line with eclipse-records certainly not due to illusion. In the great "anvil protuberance" disclosed 7th August 1869, Dr. Lewis Swift saw "many black lines crossing in different directions, and inasmuch," he added, "as they must have been, at least, fifty thousand miles long and a thousand miles broad, it would appear to be important to understand the cause of this phenomenon, and (to ascertain) if these markings are always present."[3] Corroborative observations were made by Alvan G. Clark and Professor George Davidson. With them may be usefully compared M. Liais's description of a black-edged but colourless prominence watched at Paranagua, in

[1] *Phil. Trans.* vol. clxxx. p. 345. [2] *L'Astronomie*, t. xii. p. 11.
[3] *Lick Reports on Total Eclipse of 1st January 1889*, p. 204.

Brazil, during the eclipse of 7th September 1858.[1] The composite effect was not due to contrast, since the obscure summit stood out alone when the bright lower portion had disappeared behind the advancing moon. These singular phenomena excited little comment, and lapsed into oblivion, so that dusky ramifications, connecting and defining prominences in the eclipse-photographs of 9th August 1896,[2] seemed entirely novel features. They were explained by M. Hansky, a member of the Russian party on the Amur, as outflows of hydrogen cooled by expansion;[3] but inadequately. Hydrogen below the temperature of luminosity is transparent, and the photographed veinings were densely opaque. They afford a hint, that will certainly not be disregarded, of the workings of unknown activities in connection with prominence-development.

[1] *Memoirs Royal Astr. Society*, vol. xli. p. 519 (Ranyard).

[2] *Phil. Trans.* vol. cxc. p. 204 (Wesley).

[3] *Bull. de l'Acad. Imp. des Sciences*, Mars 1897, p. 253.

# CHAPTER X.

## THE CHROMOSPHERIC SPECTRUM.

THE spectrum of the chromosphere is almost purely discontinuous. It is composed of detached bright lines. Some of these are always present, but the majority come and go. We will consider first the permanent radiations.

The chief of these are readily identified; they belong to hydrogen, helium, and calcium. Thirty hydrogen lines have been seen or photographed in dispersed chromospheric light, all members of the original, or "Huggins series," which attained nearly to its theoretical limit on plates exposed by Mr. Evershed during the Indian eclipse of 1898. The fundamental C ($H\alpha$) is the brightest. To its intensity is due the crimson glow of chromosphere and prominences; and prominences viewed spectroscopically on this line appear larger than when imaged in any of the other qualities of hydrogen-light. This is generally explained by the influence of temperature, a higher degree of heat being needed to give complete development to forms of shorter wave-length.[1] A comparatively moderate chromospheric temperature would thus be indicated. But there may be other influences in question. Professor J. J. Thomson made the significant observation in 1895[2] that the red and green lines of hydrogen show marked differences of intensity at the two electrodes of vacuum-tubes, the red predominating on the positive, the green on the negative side of a partition. The hint must indeed be reserved for future use. We are not yet in a position to apply it profitably.

[1] Frost-Scheiner, *Astronomical Spectroscopy*, p. 189.
[2] *Proc. Royal Society*, vol. lviii. p. 255.

The helium-spectrum of the chromosphere also gives rise to some interesting considerations. For its various constituent series are not represented indiscriminately at the edge of the sun. These series, we may remind our readers, are six in number, and they are distributed with beautiful precision into two corresponding triple systems. They may be distinguished for convenience as "yellow" and "green," $D_3$ giving the *tone* to the former, several vivid green lines characterising the latter set. In the laboratory, as we have seen, they are inseparable; one set cannot, by any artifice so far devised, be procured apart from the companion set. But it is otherwise in the sun. Yellow helium is always present in the chromosphere and prominences; green helium only about one-fourth as often as it is looked for. The permanent chromospheric lines are four, namely, one far down in the red at $\lambda$ 7065, the familiar $D_3$, a deep blue ray at $\lambda$ 4472 (formerly known as "*f*"), and the ultra-violet "leader line" of the principal series at $\lambda$ 3889. These have probably many associates of still shorter wave-lengths; but photographic data are too scanty as yet for purposes of discrimination between the constant and the occasional elements of the spectrum. They do not proceed, it must be borne clearly in mind, from two substances, but from one indivisible form of matter, differently conditioned. In what way, it is not easy to imagine. Laboratory experiments show that the green set of lines gains relatively in brightness with rarefaction, although the yellow set persists as well to the limit of practicable exhaustion. This indication, however, does not open a way out of the chromospheric difficulty. The gases near the sun are of inordinate subtlety. Helium ought there, if this alone were the determining quality, to be in the *green* state. Its most fundamental emanation, nevertheless, is $D_3$. Nor is its dominant position compromised in the highest prominences. On the contrary, the green rays nearly aways proceed from lower lying, and therefore from denser strata than the yellow.[1] Supplementary influences are then active—temperature, mode

[1] Some American photographs taken during the eclipse of 28th May 1900 (*Astroph. Journ.* vol. xii. p. 63) show a brightening upward from the limb, as if through increased rarefaction, of a few lines belonging to green helium. This behaviour runs in the direction indicated by vacuum-tube experience.

of illumination, admixture of foreign materials. To this latter cause of spectral modification, helium, we know, is abnormally sensitive.[1] And it is quite possible that some of the series emitted by it may be more liable to suppression than others, in which case the emergence of the yellow without the green set would be an effect of damping, not of density. It must, nevertheless, be admitted that what little relevant experimental evidence there is, scarcely countenances this surmise. The complex spectra derived by Professors Liveing and Dewar [2] from the volatile residuum which survived the freezing-out of the main constituents of atmospheric air, included rays taken impartially from all the helium-series. No quantitative analysis of the contents of their tubes was, however, possible; and the fact has been otherwise learned that the helium-ingredient of a blend must be predominant to become spectroscopically conspicuous. Every volume of hydrogen present in the chromosphere (neglecting the effect of metallic vapours) should thus probably be diluted with two volumes of helium; constituting the solar appendage largely a helium envelope. This important piece of information was brought within reach only by terrestrial observation of the new element captured from clevite.

The significance of calcium in its chromospheric relations has only of late been fully recognised. And this for an obvious reason. It is represented by only one pair of lines—bright H and K—and these are so near the limit of visibility that they could be effectively studied only by the aid of photography. They were indeed registered as leading features of the chromospheric spectrum by Professor Young in 1872; but he was entirely incredulous as to their calcium origin, holding it impossible that a substance with a vapour density forty times that of hydrogen should mount to at least equal elevations above the sun's surface. Sir Norman Lockyer,[3] on the other hand, maintained them to be characteristic of a subtle dissociation-product of calcium, alleging in support of his view the progressive enfeeblement of the "blue line" of calcium ($\lambda$ 4227), concurrently with the enhancement of H and K, as the substance was more and more completely

[1] See *ante*, p. 60. [2] *Proc. Royal Society*, vol. lxvii. p. 467.
[3] *The Chemistry of the Sun*, p. 194.

decomposed at each addition of intensity to the electric current transmitted through the vacuum tubes. The case for dissociation appeared strong; it has, nevertheless, broken down. Sir William and Lady Huggins in 1897 successfully reduced calcium to the "two-line" condition by attenuation alone.[1] Thus the enigmatical prominence-spectrum of calcium was at last artificially produced, and no escape was left from the identification with true metallic calcium of the form of matter encompassing the sun with violet radiance.

A formidable problem, however, remained. Calcium near the sun seems to possess a *levitating* faculty altogether inexplicable. It floats as high up as hydrogen, or even overtops it. H and K are the most diffusive of all the prominence-rays; they are derived from the summits of the tallest flames, and from every fibre of their texture. This anomalous agility in a comparatively heavy metal must, according to the late Professor Keeler,[2] be the index to some remarkable property unrecognised by ordinary chemical methods. Unless, indeed, something analogous to electrolytic action be in question. There is much to be said in favour of M. Deslandres's opinion that the chromosphere is electrically luminous;[3] and if so, then "ions," not molecules or atoms, are presumably its constituting particles. But ions are on a Lilliputian scale of magnitude, and they may be of nearly the same mass for all the chemical elements. Here, however, we trench upon a region of pure speculation. A region, nevertheless, that is likely ere long to be annexed, in part at least, to surveyed territory, since pioneers are actively engaged there. Much, in the interpretation of solar phenomena, depends upon the results of their work; for here, as in every department of astrophysics, the experimental decisions of terrestrial physics must be awaited, not anticipated.

The three ingredients of the chromosphere so far spoken of—hydrogen, helium, and calcium—are found as well in its

[1] *Proc. Royal Society*, vol. lxi. p. 433. Besides H and K, *echoes* of them survive in a pair situated so high in the ultra-violet that they can only be photographed with a specially adapted apparatus. Their wave-lengths are $\lambda$ 3179 and $\lambda$ 3159. They may or may not be chromospheric lines. The records so far obtained do not extend to their remote position.

[2] *Bulletin of the Yerkes Observatory*, No. 4, 1897.

[3] *Observations de l'Éclipse Totale du Soleil du 16 Avril*, 1893, p. 64.

eruptive outgrowths. Gaseous prominences of all sorts and sizes are thus triply compounded. But we have now to consider a form of matter permanently present in the chromosphere, though rarely projected to any considerable altitude above it. Its badge is a single green ray, which has a curious history. It was momentarily identified with an auroral line; it was long erroneously identified with the distinctive corona-line. It is apparently reversed in the sun—that is to say, a Fraunhofer line falls just in its place. This is Kirchhoff's "1474" (known as 1474 K), which has proved, under close scrutiny, to be triple. It results from absorption by iron, by cobalt, and by an unrecognised substance. Now the chromospheric ray agrees in position with the iron line, which is one of secondary importance; yet it cannot at present be asserted confidently that it really emanates from glowing iron-vapour. If it did, it should be ordinarily associated with other iron-lines, and none have been ascertained to make part of the fundamental chromospheric spectrum. The vapour giving out "1474 K," however, is never absent from the solar envelope,[1] although it perhaps subsides at times into its lower strata.[2] On the other hand, it occasionally rises in metallic prominences to a height of about fifteen thousand miles. Mr. Lord, at the Lick Observatory, observed the enigmatical line ($\lambda$ 5316·8) as shining vividly at the base of a violently disturbed prominence on 4th August 1892,[3] and Mr. Evershed records similar experiences. Dr. Fényi caught a still rarer effect on 19th February 1892 in a prominence attending the great spot-group then visible.[4] The object was peculiar, though not unique, in showing complete forms built up of the various metallic and other substances injected into it from below. Fig. 14 reproduces an instructive drawing made on the spot. The bottom sketch was taken on the C-line when the eruption was at its height. It reached an elevation of 56,000 miles. The over-arching of three filaments towards a point at some distance from the base is noteworthy. The second drawing in Fig. 14 is of a date twenty-four minutes later than the first. It depicts the flame

[1] Hale, *Astroph. Journ.* vol. v. p. 225.
[2] Evershed, *Nature*, 9th Sept. 1897.
[3] *Astr. and Astrophysics*, vol. xi. p. 738. [4] *Ibid.* p. 430.

in "parhelium" light. The image viewed was constructed on the *red* ray of "green" helium. This was much smaller than the simultaneous hydrogen-image, and that obtained on the "1474" line had shrunken still further. But it was measured at half-past ten, an hour after the drawing on "C" had been made, when the first vehemence of the outburst had

On 1474 K. $10^h\ 25^m$. Height = 88·3″.

On λ 6677. $9^h\ 44^m$. Height = 39·4″.


On C-line, 17th Feb. 1892, $9^h\ 20^m$. Height = 124″.

FIG. 14.—Forms of a Prominence in Hydrogen, Helium, and Pseudo-Coronium (Fényl).

subsided. The line 1474 K is singularly exempt from displacement effects through motion. It remains erect and undeviated in the midst of solar storms. Nor does it widen perceptibly with increase of pressure downward. Its invariable . fineness contrasts remarkably with the wedged shape near the photosphere of C, H, and K. Unusual agitation is betokened by its emergence in prominences.

Eclipse-spectrographs do not include it, while they have

afforded some other quite unexpected results. Of special consequence is Mr. Evershed's detection of titanium as an unfailing chromospheric element.[1] Plates exposed by him in India, 22nd January 1898, proved to be crowded with ultra-violet lines belonging to this metal. Some among them had indeed been already recognised by Mr. Jewell in Professor Hale's daylight photographs of prominence-spectra.[2] The height to which they extended indicates a diffusiveness for titanium-vapour equal to that of hydrogen and helium, although inferior to that of calcium. Its atomic weight on the hydrogen scale is 48; it is just as much lighter than iron as it is heavier than calcium. But comparative vapour-densities are, so to speak, impotent for the regulation of elemental distribution near the sun. Another surprise afforded by the Indian eclipse was the conspicuous presence in the chromosphere of scandium as well as of manganese and chromium; while Mr. Hartley[3] has identified as another of its constituents the rare metal gallium from two of its characteristic lines ($\lambda$ 4172 and $\lambda$ 4033) recorded during the eclipse of 1893.

On 29th September 1897, Professor Hale, using a grating spectroscope on the forty-inch Yerkes refractor, discerned the green carbon fluting bright at the edge of the sun.[4] Two years later, he found the corresponding yellow band, although the third in the blue remained imperceptible. He inferred the permanent existence near the sun of a shallow layer of carbon vapour.[5] Its rays do not come near the surface; they have to be *dredged for*. Hence the extreme delicacy of detective observations. The anomaly of this behaviour on the part of carbon is glaring. Its specific lightness ought to carry it to altitudes far beyond those attained by titanium and calcium. Yet it lies sunken almost out of sight, while they float manifestly aloft. Some other sorting-out influence besides that of gravity palpably comes into play in the chromosphere and prominences. The possession by the sun of a carbon-envelope, which, although thin visually, must really be at least 500, and may well

[1] *The Indian Eclipse*, p. 70.
[2] *Astroph. Journ.* vol. xi. p. 243.
[3] *Ibid.* p. 165.
[4] *Ibid.* vol. vi. p. 412.
[5] *Ibid.* vol. x. pp. 112, 287.

be 1000 miles in depth, has an important bearing upon the vexed question of photospheric constitution, and tends to strengthen a barely indicated analogy between the sun and a peculiar class of red stars.

The chromospheric spectrum, when its adventitious elements are reckoned in, is highly complex. During a few weeks of 1872, Professor Young, by vigilant watching, determined 273 lines seen, in the clear air of the Rocky Mountains, to flash out intermittently, one by one, or in companies together. And this first systematic enumeration was subsequently greatly extended by its author, while crowds of ultra-violet lines have been added by the photographic investigations of Hale, Deslandres, Evershed, and others. For the most part the rays brightened in eruptions are reversals of Fraunhofer lines, picked out largely at haphazard, yet with an obvious preference, expressly noted by Sir Norman Lockyer, for such as are vivified when the higher excitement of the spark is substituted for the arc in laboratory experiments. This has been taken to imply that the chromospheric is essentially a high-temperature spectrum; but the facts may be differently interpreted.

Among the elements most apt to shine evanescently in metallic prominences are sodium, magnesium, "green" helium, barium, iron, vanadium, and strontium. Gigantic ragged forms, especially when they appear in high latitudes, are of relatively simple chemical composition; or it may be that their condition favours the visibility of only the most persistent radiations. Small compact prominences yield, at any rate, much richer harvests to gleaners of spectroscopic novelties. A specimen of this class was observed by Father Sidgreaves, 10th September 1891.[1] It presented the aspect of "four blow-pipe jets intensely bright at the bends," was 16,000 miles high, and lasted only an hour. Twenty-six brilliant lines were counted in the visual part of its spectrum, the invisible part, in the absence of suitable appliances, remaining unrecorded. The shape of this flame was equally well defined in *both* the red rays of helium, and appeared nearly the same in sodium and magnesium. The spectral peculiarities of such objects, however, are most marked in the ultra-violet. A

[1] *Astr. and Astrophysics*, vol. xi. p. 66.

photograph taken at the Kenwood Observatory, 15th October 1892, registered, from an undistinguished prominence, no less than seventy-four bright lines between the wave-lengths 3970 and 3630,[1] most of them being of unknown origin. But since then it has become possible to identify a dozen and upwards with rays measured in the spectra of krypton and xenon by Professors Liveing and Dewar;[2] and the circumstance seems to associate those scarce atmospheric gases with helium as chromospheric constituents.

Occasionally, under circumstances not yet defined or understood, prominences emit continuous light. The sheeny white objects sometimes seen under cover of the moon's shadow owe their peculiarity to this cause. The whole gamut of prismatic radiance is derived from them, with the addition of bright H and K and a suspicion of hydrogen lines. Thus they are essentially calcium-forms interpenetrated with glowing *dust*. Their light is probably original. If it were reflected, traces of Fraunhofer-absorption which seem to be missing should be perceptible. Distinctively "white" prominences are not common; none were observed during the totality of 28th May 1900. But "red" prominences differ considerably in colour-intensity, all the ruddy shades, from deep ruby to pale pink, being represented in them. Many perhaps consist of a crimson core veiled in almost colourless material. Certainly all are not equally well seen in and out of eclipse. From a comparison of drawings made during the totality of 1870 with his own simultaneous daylight observations, Tacchini inferred that the spectroscope disclosed only the cores of flame in such objects;[3] and the experience was repeated on the occasion of the Egyptian eclipse of 17th May 1882. The four prominences then measured were of a rosy tint, lightening towards the margins, which looked as if edged with a lustrous fillet. "These results," Professor Hale writes, "may be accepted as establishing an important difference between the spectroscopic and eclipse-images of prominences." Nevertheless the difference is not constantly present. Some chromospheric forms are identical, viewed prismatically at the

[1] *Astr. and Astrophysics*, vol. xi. p. 821.
[2] *Proc. Royal Society*, vol. lxviii. p. 396.
[3] See a valuable discussion by Hale, *Astroph. Journ.* vol. iii. pp. 374-387.

edge of the sun, or directly in the dark beside the occulting moon. These are, of course, purely gaseous; the others presumably give a mixture of continuous and discontinuous light.

A very curious feature of the prominence-spectrum was ascertained by Mr. Evershed during the eclipse of 1898.[1] It *becomes* continuous in the extreme ultra-violet. The range of unbroken radiance begins abruptly just where the hydrogen series ends (near $\lambda$ 3668), and extends to the limit of the plate's sensitiveness. Not even a guess can be hazarded at the physical condition underlying this radiative vagary. A different cause must be ascribed to certain local outbursts of white light in eruptive prominences.[2] This symptom of disturbance has been interpreted by Professor Hale as follows. "Objects of the kind," he says,[3] "are closely related to faculæ, and probably rise from them. It thus occasionally happens that a violent eruption carries some of the white-hot particles to a considerable distance above the photosphere. In such a case the prominence gives a continuous spectrum in addition to its bright lines." The explanation may pass muster, since no better has been offered.

M. Deslandres succeeded in showing, early in 1892,[4] that the sun may, in a restricted sense, be designated a "bright line star"—that is to say, he elicited from the aggregate of its light evidence of gaseous emissions. Treating the sun as a star by admitting into his spectrographic apparatus the whole of its rays simultaneously, he obtained vivid reversals of the violet calcium lines. But this is only possible when the calcium flames crowning faculæ are widely and strongly developed. Ordinarily their emissions are drowned in the surging flood of continuous radiance. But facular maxima recur, coincidently with spot-maxima, once in about eleven years; so that the periodicity of the sun might conceivably be determined by this one feature at distances obliterative of all other signs of disturbance. Not that the sun viewed, say, from Sirius, could with our actual appliances be detected, even

[1] *Phil. Trans.* vol. cxcvii. A, p. 399.

[2] *Astr. and Astrophysics*, vol. xi. p. 431; *Comptes Rendus*, 17th Aug. 1891 (Fényi).

[3] *Astr. and Astrophysics*, vol. xiii. p. 119.

[4] *Comptes Rendus*, 25th July 1892; *Knowledge*, vol. xvi. p. 146 (A. M. Clerke).

at culminating epochs of agitation, as a bright-line star. Some of his fellow-stars, however, may be in a greatly enhanced stage of his condition, and we may learn to follow their vicissitudes by spectrographic observations of the alternate glimmering and fading of fine rays projected upon the deep shadow of their calcium-absorption. Thus the means may be afforded of ascertaining the flow of change in remote and gigantic orbs; and we shall perhaps in the future be better acquainted with the cyclical peculiarities of Capella or Arcturus than with those of our own "particular star."

# CHAPTER XI.

## THE CORONA.

THE corona is exclusively an eclipse phenomenon. No sooner is totality established than it is there. It seems to have emerged from nothingness, to have arrived from nowhere. It starts into view with the abruptness, the inexplicableness, of an apparition. "The sun," Professor Langley says, recording his impressions of the eclipse of 1869, "went out as suddenly as a blown-out gas-jet, and I became as suddenly aware that all around where it had been, there had been growing into vision a kind of ghostly radiance, composed of separate pearly beams, looking distinct each from each, as though the black circle where the sun once was bristled with pale streamers stretching far away from it in a sort of crown." [1]

The corona presents various aspects, but it may always be described as composed of extended streamers springing from a much more intensely luminous ring, the so-called "inner corona." There is no real separation; the entire appendage is evidently framed on the same constructive principle; yet the distinction is obvious visually, and convenient descriptively. "I do not know," Mr. Francis Galton wrote of the corona visible 18th July 1860, "to what I can justly compare that magnificent meteor. It differed from other objects in the remarkable whiteness and purity of its light, and also in the definition of its shape as combined with a peculiar tenderness of outline." [2] Both he and Winnecke noticed the curvature of some "long arms of light" protruding from the ring, while other rays took "a more or less tangential direction." Mädler

[1] *The New Astronomy*, p. 40.
[2] *Memoirs Royal Astr. Society*, vol. xli. p. 563 (Ranyard).

was struck with the *determinateness* of the formation. What he saw was no vague light-effusion, but a congeries of sharply terminated beamy sheaves. This is a radical characteristic. The solar corona is a texture of significant pattern. There is indeed much difficulty in laying bare the original design. A spherical agglomeration projected on a plane gives rise to intricate effects of perspective, from which the true relations in solid space of the objects originating them can be deduced only by careful and systematic interpretation on strict geometrical principles. The problem was attacked by Professor Schaeberle[1] with the help of an ingeniously contrived model, photographs of which showed divergent rods inserted over the surface of a globe as apparently intercrossing and interlacing in the flat picture imprinted on the plates. It is, however, well to remember that, while curved rays may be projected so as to seem straight, straight rays can never appear curved. Beams that show flexure are inflected. Nor can a semblance of double curvature be given by perspective to those bent simply in one direction; moreover, rays that are actually normal to the sun's surface must, from all points of view, appear radial to the limb.[2]

Coronal structure is of immense variety. It is intrinsically of a radiated character, and the fact is of primary importance. There are no signs of concentric arrangement;[3] coronal materials do not form shells or envelopes, such as surround the heads of comets; they are, on the contrary, drawn out into fibres by forces acting upon them in minute detail. Comparisons to spun glass and to silken filaments indicate the delicate nature of the shining tissue spread round the obscured sun. There are indeed differences. The fibres sometimes, as in the corona of 22nd December 1870, look to have been "combed out," but more or less of derangement is usually prevalent. Tangled hanks of thread are often suggested, or "masses of luminous hair in disorder."[4] These contorted forms, although their complexity is doubtless augmented by the superposition of sundry groups of twisted rays presented at different

[1] *Publications Pacific Society*, vol. ii. p. 68.
[2] *Memoirs Royal Astr. Society*, vol. xli. p. 656.
[3] Ranyard, *ibid.* p. 652.
[4] *Ibid.* p. 589 (Pope Hennessy).

angles, afford remarkable evidence of disturbance within the corona itself. Their photographic registration dates from the Sumatra eclipse of 18th May 1901. On plates there taken with the Lick forty-foot telescope, and by Mrs. Maunder at Mauritius, a tumultuous area, agitated as if by the effects of an explosion, was strikingly depicted. "A long thread-like prominence appeared," it was stated, "to emanate from the same source."[1]

Fleecy coronal tracts are at times intermixed with regions of striation. The corona of 1868 was perceived at Masulipatam to be "slightly mottled" near the sun, and the "curdled" aspect of the great nebula in Orion has often been recalled to telescopic observers. Sir Norman Lockyer, at Baikul, 12th December 1871, was struck with an "exquisite" and "strongly-developed structure." "I at once," he continued, "exclaimed 'Like Orion!' Thousands of interlacing filaments varying in intensity were visible; in fact, I saw an extension of the prominence-structure in cooler material."[2] It may be remarked that nebular tufts, no less than prominence-jets, are resolvable into fibres under the best conditions of seeing. The aureola of 1871 was of such incomparable beauty that M. Janssen could scarcely rouse himself from its delighted contemplation to carry out his programme of work. Numerous coral red prominences were relieved against the "velvet white" of the corona, the exterior shape of which was rudely quadrilateral. Interiorly the streamers leaned together in pairs so as to imitate flower petals, the general effect resembling that of a gigantic lucid dahlia, with the black moon for its heart.

Again and again, in descriptions of successive coronas, the Orion-similitude recurs. In the "density, brightness, and species of its light," that of 1st January 1889 strongly reminded a Nevada State observer of the nebula, and its slightly greenish tinge of colour completed the likeness.[3] Again, in examining the coronal photographs of 9th August 1896, Mr. W. H. Wesley detected an area "broken up by dark channels into flocculent-looking masses, giving to it somewhat of the *curdled* appearance of some parts of the

[1] Perrine, *Lick Bulletin*, No. 9.

[2] Ranyard, *Memoirs Royal Astr. Society*, vol. xli. p. 687.

[3] *Lick Reports*, p. 193.

nebula in Orion."[1] The similarity is not merely superficial. Laborious photographic comparisons by Mr. Ranyard (assisted by Mr. Wesley) emphasised the organic analogy between the great nebula and the solar corona.[2] Synclinal forms (as the petal-shaped structures are called) emerge in both, and the branching effusions round the trapezium seem to mimic details legible in many eclipse-pictures.

A chain of "pearly cones" furrowed spirally, 200,000 to 300,000 miles in height, and rising above a long bank of red prominences, were perceived by Professor Cleveland Abbe in the corona of 1869. And in 1893 the sun appears to have been fringed in this manner nearly all round, the individual peaks being projected together into such close array as to be in many places undiscernable apart. "Systems of (approximately) concentric arches" were also distinguished by Professor Schaeberle in his large-scale photographs of the same eclipse.[3]

Inverted shapes are also, though less commonly, met with. Paraboloids, convex towards the limb, now and then replace arcs and cones based upon it. A curious instance was afforded by Schaeberle's "coronal comet" of 16th April 1893.[4] This object seemed as if *spitted* upon a slender, solitary, nearly radial streamer, from which it had evidently developed. It was not the only specimen of its class. A well-known drawing by Liais of the corona of 7th September 1858 shows an immense double paraboloid lying behind and partly hidden by a "dahlia petal." The vertex seemed to be just at the limb. A somewhat similar dusky arc was seen by Winnecke in the corona of 1860.[5] It looked, he said, like a tracing in sepia. Again, during the eclipse of 1868, a bright parabolic outline, "with its vertex towards the sun," was noted by Weiss. Finally, Homer Lane observed at Des Moines, Iowa, 7th August 1869, two condensations of light which "might well be compared to small telescopic comets, with tails of some length, but without a head, and with no distinct indication of a head at one end rather than the other. They were not far from radial in direction relatively to the sun's

[1] *Phil. Trans.* vol. cxc. p. 204. [2] *Knowledge*, vol. xii. p. 145, 1889.
[3] *Report on the Eclipse*, p. 96. [4] *Ibid.* p. 100; *Observatory*, vol. xvii. p. 350.
[5] *Mémoires Acad. de St. Pétersbourg*, t. iv. p. 38, 1862.

centre, and had their origin above the limb of the moon."[1] He estimated the length of each at about 130." These appearances are full of meaning. They plainly assert the subjection of coronal matter to a dual repulsion, such as acts upon the "crystal tresses" of comets. A local centre of condensation throws off a filmy envelope, the constituent particles of which, as they approach the sun, are swept backward into a train by a counter influence proceeding from him. The only genuine "eclipse comet" so far captured was that seen and photographed at Sohag, 17th May 1882. It was sharply characterised as such, the effects of swift motion being unmistakably impressed upon its curved plumage.

An eclipse, visible in the Western States of North America, 29th July 1878, disclosed a surprising spectacle. In lieu of the ordinary radiated corona there were seen "bristles" of light at the sun's poles, enormous "wings" at each side of the equator. Professor Langley observed the phenomenon from the summit of Pike's Peak in Colorado, at an elevation of 14,000 feet in a stainless sky. Thus favourably circumstanced, he was able to trace one wide beam to a distance of about five millions of miles from the sun, the other fully twice as far.[2] The direction in which they lay proved, when carefully measured, to agree closely with that of the zodiacal light, and "a faint central rib" emphasised the coincidence. "With the telescope," he says, "the whole of the bright inner light close to the sun was found to be made up of filaments, more definite even than those seen in sun-spots," and apparently exempt from the effects of spherical projection; they "fringed the sun's edge in definite outline, as though it were really but a disc."

At the time of this eclipse, the sun was in a state of exceptional tranquillity, and a search through the solar archives brought out the notable fact that a similar apparition had, eleven years previously, spots then too being nearly extinct, been described and depicted by Grosch of Santiago. He inferred from it the possession by the sun of "strong magnetic polarity." And indeed the divergent light-fibres at the poles, in 1867 no less than in 1878, seemed to trace precisely the lines of force in a magnetic field. The con-

[1] *Memoirs Royal Astr. Society*, vol. xli. p. 602.
[2] *The New Astronomy*, p. 55.

currence of these phenomena with critical epochs in the sun's activity started the idea, due, in the first instance, to Mr. Ranyard,[1] of varying coronal types. It was amply borne out by subsequent experience. From eclipse to eclipse, throughout the eleven-year cycle, the corona exhibits changes of form in marked conformity to spot-vicissitudes. In the accompanying plate, the original of which is by M. Hansky, the coronas of 1860, 1870, 1883, and 1893, all of pronounced maximum type, are represented in the first column; those of 1867, 1878, and 1889 in the third. The second and fourth show coronas of intermediate forms. The last figure in the third column has a prophetic character. It shows M. Hansky's anticipation of the kind of halo due, on the theory of recurring types, in 1900. What was actually photographed is given for comparison in Plate VI., Fig. 1. The correspondence leaps to the eye. A definite law of variation indeed quite obviously regulates the shape of the effluence about the sun. At spot-maxima its component streamers issue from all latitudes indiscriminately; they pay little or no regard to heliographic co-ordinates. Then, as disturbance relaxes, they gradually draw away from the poles, and tend to form "synclinals" above the spot-zones, giving to the whole appendage the "form of a four-rayed star, the points of which are inclined 45° to the sun's axis."[2] In the polar regions abandoned by them, "magnetic" filaments meanwhile become noticeable, and what may be called the intermediate type is constituted. It is subject, however, to indefinite variations of detail. A good example is shown in Plate VII., Fig. 1, from photographs taken on the Amur, 9th August 1896, by a Russian party under the leadership of M. Bélopolsky.

One ray, it will be noticed, is greatly longer than the others, and the same peculiarity distinguished the corona of 1898. Only when the tide of solar agitation is dead out, is the finished type of minimum aureola realised. We have then a symmetrical arrangement of crested poles and equatorial extensions, with this one singular qualification to its symmetry, that the wings are not a pair. One is formed of convergent, the other of parallel, or even divergent rays. And they seem to be

[1] *Memoirs Royal Astr. Society*, vol. xlvi. p. 238.

[2] Young, *The Sun*, p. 264.

reversed east and west at alternate epochs. Both are radically double; they are formed by the closing down upon the equator, as spot-activity becomes exhausted, of the synclinal groups previously visible in middle latitudes. It is difficult to realise that these "wings" are merely the profile-shapes of a vast luminous disc completely encompassing the sun. Hence an extreme intricacy of structural details most baffling to efforts towards interpretation.

Coronal modifications are not so entirely isolated as might at first sight appear. Looked at more closely, they are perceived to correspond unmistakably with the cyclical changes in distribution of surface disturbances. This was insisted upon by M. Bélopolsky in 1897.[1] Spots descend into lower latitudes with the approach of each minimum. One after the other, the eleven-year waves of commotion attain their acme in medium zones, and die out near the equator. Coronal development pursues the same course. Its most intimate relations, however, are with chromospheric eruptions. Tacchini [2] was the first to notice that coronal outflows emanate from regions frequented by prominences, which at times of maximum spread all over the sun, but near minimum withdraw from the extensive polar tracts simultaneously denuded of far-spreading streamers. Particular agreement frequently accentuates this general correspondence. Thus the springing of a coronal arch has usually a prominence for its motive. Each pearly pavilion is erected over a red flame. Coincidences of the kind are of perpetual occurrence. Chromospheric jets seemed (and doubtless were) appropriated individually to the "striated cones" observed by Cleveland Abbe in 1869. In Schaeberle's fine photographs of the eclipse visible in South America 16th April 1893, one-sixth of the sun's circumference came out clear of prominences; and just over the same segment there is a gap in the elsewhere unbroken range of coronal arches.[3] In some cases arches are buttressed upon prominences; in others they are symmetrical as regards them; coronal streamers appear to be vaulted into domes, or bent together into ogives, through effects of

[1] *Bull. de l'Acad. de St. Pétersbourg*, t. vi. p. 286.
[2] *Atti dell' Accad. dei Lincei*, 1889, p. 763.
[3] Schaeberle, *Report on the Eclipse of 16th April 1893*, pp. 92-98.

eruptive action in the chromosphere. These relations were especially marked in the corona of 1896. The wide polar rifts were devoid of prominences, but a prominence lay at the root of each great streamer, and a prominence was enclosed by each synclinal structure. These M. Hansky inferred, from their interior darkness, to be hollow,[1] like the tails of certain comets; and he noticed curious effects of coronal transparency, a few beams showing traceably through the substance of those in front of them. The correlation of prominences with coronal forms was somewhat less conspicuous in 1898 than in 1896, and was barely perceptible in 1900. The Lick photographs of 1901, however, showed the envelopment of a prominence by a "series of coronal hoods," besides other symptoms of community in disturbance between the chromosphere and the silvery aureola.

The more closely the spectrum of the corona is studied, the more interesting and enigmatical it becomes. It has a triple origin. Continuous reflected light is mixed up in it with continuous original light, and these again with bright-line emissions. The three elements are not easily separated, and the proportions of them present vary from time to time. The gaseous spectrum is feeble, especially near spot minima. Its leading constituent is a green line at $\lambda$ 5303, long confounded with the chromospheric $\lambda$ 5317. Their disconnection first became apparent in Mr. Fowler's eclipse photographs of 22nd January 1898, and was announced by Sir Norman Lockyer[2] as one result of their examination. The green line characterises the unknown substance designated "coronium," the distribution of which round the sun can be investigated by its means. Photographs taken during totalities with the "prismatic camera" give separate images of the solar appendages in each quality of discontinuous light emitted by them, and the "green" coronal image proves to be approximately ring-shaped. The gas it is derived from seems to spread through the "inner corona" to an average height of from 160,000 to 200,000 miles, but not to extend into the sheaves and streamers beyond. There are indeed irregularities. The annulus of coronium is far from being uniform or homo-

[1] *Bull. de l'Acad. de St. Pétersbourg*, t. vi. p. 253, 1897.
[2] *Nature*, vol. lix. p. 529.

geneous. It is wider, perhaps also more condensed, in some places than in others, and spectrograms taken with a slit by Professor Campbell at Jeur suggested, by the distortions of the characteristic ray impressed upon them, the progress of radial movements, such as might well be deemed inevitable in an aerial envelope obviously not in a state of equilibrium.[1]

Ten or a dozen coronal lines besides the green ray have been photographed. The wave-lengths of the most authentically recorded are as follows: 4232, 4086, 3987, 3801, 3643, 3456, 3388, and 3381. No success has hitherto attended efforts to arrange them in a series; nor is it by any means certain that all claim the same chemical origin. On the contrary, the fundamental green line, together with the most refrangible of those above enumerated, appears capable of segregation from the violet ray $\lambda$ 3987 and the first three of its ultra-visible associates.[2] Two strange gases then, at any rate, are indicated as co-existing in the corona. And they are unmixed with any familiar substance. Evidence collected during recent eclipses testifies strongly to the absence of all the chromospheric materials. Not even the pervasive trio, hydrogen, helium, and calcium, extend into the vast solar halo. Some of their radiations, notably H and K, have *seemed* to be derived from it, but only through the effects of atmospheric scattering. They come as well from the black disc of the moon. Probably only some peculiar forms of matter, or forms of matter in a peculiar state, constitute the gaseous corona. So far coronium has not been recognised elsewhere.

The continuous light from the interior halo is mainly original. It emanates from incandescent solid or liquid particles. But their incandescence appears to be of an unusual kind. Bolometric experiments, carried out by Messrs. Abbot and Mendenhall of the Smithsonian Observatory during the eclipse of 1900,[3] showed the coronal beams to be almost wholly wanting in thermal power. Compared with them moonlight is a potent source of heat. They include, according to the results in question, next to no infra-red waves, and are surmised to be comparable in quality to the glow of phosphorescent or luminescent substances. Novel inquiries in the laboratory

[1] *Astroph. Journ.* vol. x. p. 190.

[2] S. J. Brown, *Astroph. Journ.* vol. xii. p. 63.

[3] *Ibid.* p. 73.

will be needed to ratify these significant conjectures; while it is to be hoped that the eclipse of 1904 will afford some positive data as to the distribution of energy in the coronal spectrum, which may serve as a basis both for photographic investigations and for theoretical conclusions.

Photospheric light *must* be reflected from the pulverulent materials of the corona, and a reflected ingredient is, accordingly, contained in its radiance. It is, however, small in quantity. Thus the dark Fraunhofer lines are barely distinguishable in it. They were detected by Janssen in 1871; fifteen were photographed by Pluvinel at Senegal in 1893.[1] On the same occasion, nevertheless, Deslandres could obtain no trace of them, and Campbell was equally unsuccessful in 1898.[2] The truth is that where the original emissions are strong they get *drowned out*. They show, and that with difficulty, only in the less luminous sections of the appendage. This was made perfectly obvious by Mr. Perrine's discussion of the plates taken in Sumatra, upon which thirty-five Fraunhofer-lines impressed themselves, but only in regions remote from the limb. Polarisation-effects give accordant testimony.[3] They are slight but unmistakable, and plainly indicate the action of scattering particles right up to the limb. Some hints as to the manner of their distribution were obtained by Professor Turner in 1898, and again in 1900, through the ingenious device of photographing the corona across a plate of Iceland spar, and so obtaining two pictures in oppositely polarised light.[4]

Much remains to be learned about the nature of coronal radiance, and the opportunities for its investigation are restricted and unsatisfactory. Yet upon their outcome success in coronal portraiture largely depends. Eclipse-photography is an art in itself, and one beset by subtle difficulties. To ensure the best results, the plates employed should have a curve of sensitiveness as nearly as possible coincident with the energy-curve of the coronal radiations, and the form of the latter is entirely unknown. Many questions too arise regarding the quality of the plates, and the development proper

[1] Frost-Scheiner, *Astr. Spectroscopy*, p. 192; *Comptes Rendus*, t. cxvii. p. 25.
[2] *Astroph. Journ.* vol. xi. p. 232. [3] Schuster, *Monthly Notices*, vol. xl. p. 35.
[4] *Observatory*, vol. xxi. p. 157.

to be given them, regarding the best kind of instrument for exposing them with, and, above all, the length of time that should be allotted to the process. And here the obstacle is encountered that no single exposure is suitable to the entire aureola. One long enough to bring out the streamers is too long for the delicate details of the brilliant interior. The choice has to be made between solarisation and incompleteness of representation. Two remedies have been tried. The first is by piecemeal delineation. From photographs of varied exposures, a picture showing the special features rendered by each is compounded by a skilled draughtsman. But it has no longer an autographic value; the forms embodied in it have been deliberately selected and unconsciously emphasised. "To a certain extent," it has been well said,[1] "the same personality enters into the examination of a photograph that is known to exist in naked-eye observations of the corona." M. Morin's drawing of the corona of 1896 (see Plate VII. Fig. 1) is a fine example of what can be done by combining multiplied photographic impressions. The two best of those availed of were taken with an ordinary camera in one and two seconds respectively; the rest with a photoheliograph, getting exposures up to thirty seconds.[2]

The alternative method is purely automatic. It was invented and successfully applied by Professor C. Burckhalter of the Chabot Observatory, California, at the eclipse of 28th May 1900.[3] In his apparatus a system of revolving diaphragms is arranged so as to give exposures graduated to correspond with distance from the sun. The image being progressively covered at successive short intervals, time is allowed for the imprinting of faint coronal extensions, while the bright parts already effectively portrayed are shielded against further prejudicial action. The photograph "controlled" in this way was a striking record, and conveyed some curious intimations of perspective effects in the mutual overlaying of tufts and beams.

The outlying branches of the corona usually baffle the perception of the sensitive plate; for they merge into a

[1] Burnham and Schaeberle, *Report on Eclipse of December 1889*, p. 38.

[2] *Bull. de l'Acad. de St. Pétersbourg*, t. iv. p. 275.

[3] *Popular Astronomy*, vol. viii. p. 369.

dimly illuminated sky-ground, from which they are, unless by special precautions, chemically indistinguishable. The most conspicuous performance in this direction was by Mrs. Maunder in 1898.[1] With a lens of only $1\frac{1}{2}$ inches in aperture, giving small but intensely bright images, exposures were experimentally made of inordinate length, proportionately to the shortness of the focus. The unprecedented result was achieved of photographing rays to a distance of nearly seven solar diameters from the limb. Mr. Wesley's drawing from the original negatives is reproduced

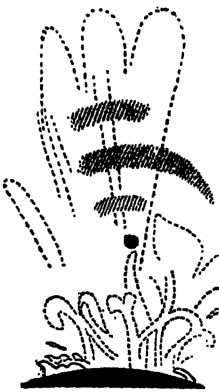


FIG. 15.—Diagram of Markings in the Corona of 1871. Drawn by W. H. Wesley (*Knowledge*, vol. xxiii. p. 225).

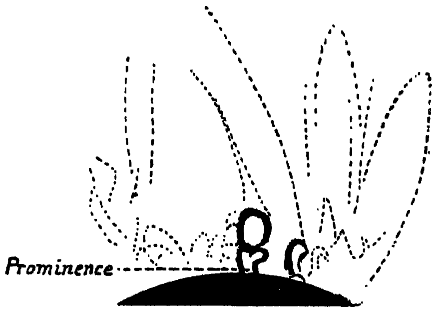


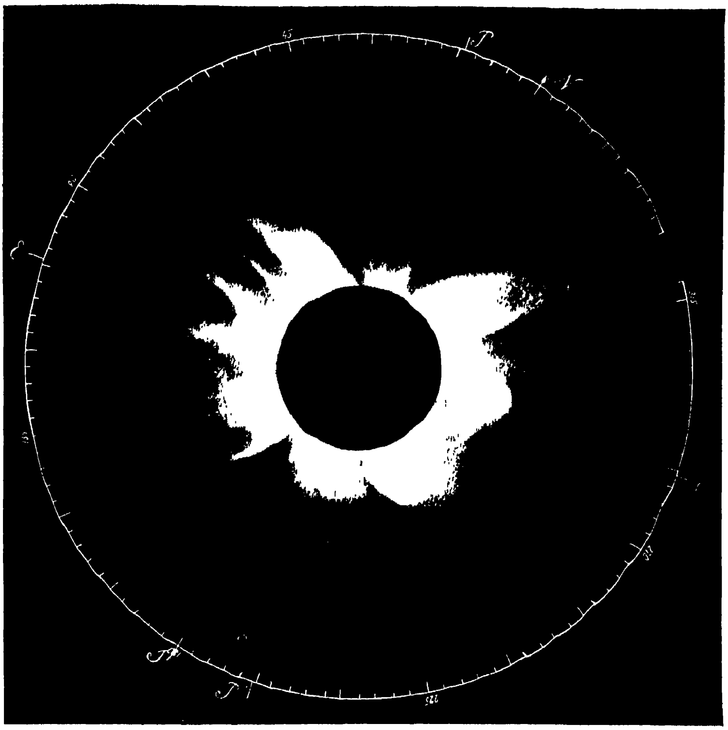

FIG. 16.—Diagram of Markings in the Corona of 1896. Drawn by W. H. Wesley (*Knowledge*, vol. xxiii. p 226).

in Plate VII. Fig. 2. Four long narrow divergent rays are visible in it, each starting outward from a synclinal structure. Mr. and Mrs. Maunder hold it probable that such structures have always rod-like extensions, needing only protracted photographic exposures to bring them into view;[2] but this is more than doubtful.

A very perplexing appearance is that of dark markings in the corona. They are not mere interspaces between brilliant rays. Mr. Wesley, who is an expert in the scrutiny and interpretation of celestial photographs, vouches for their reality. Figs. 15 and 16 copy his diagrams of obscure streaks and veinings in the coronas of 1871 and 1896. In the first

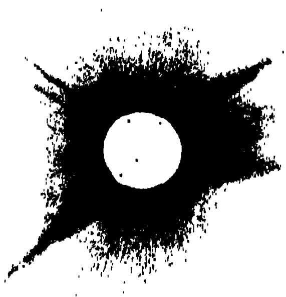
[1] *The Indian Eclipse*, p. 114. [2] *Ibid.* p. 118.

1.



SUN'S AXIS, NORTH.

WEST.
SUN'S EQUATOR.



SUN'S EQUATOR
EAST.

SOUTH, SUN'S AXIS.

1. The Corona of 1896. Drawn by M. Morin from Photographs taken on the Amur.
2. The Corona of 1898. Drawn by W. H. Wesley from Photographs taken by Mrs. Maunder. (*Knowledge*, vol. xxi. p. 108.)

*N.B.* The sun's axis meant to be indicated is a *vertical* line bisecting the disc, with which the north-and-south line makes a small angle

case, they cut right across the lustrous branches of the halo; in the second, they are in obvious connection with prominences. Indeed, black coronal and black chromospheric forms belong undeniably to the same order of effect, and cannot be separated causally. They took another shape in the corona of 1900. Mr. Wesley's beautiful drawing from Mr. Maunder's photographs (see Plate VIII.) shows rifts apparently darker than the general background of the sky, and hence of a *positive* character. Their substantial presence was confirmed [1] by negatives taken at Wadesborough, U.S.A., by Miss Gertrude Bacon; but the difficulty of accounting for them is at present insurmountable. That they are due to the interposition of opaque bodies can scarcely be admitted. The objections are prohibitive. Yet the phenomenon is none the less genuine for being incomprehensible. We must wait and compare.

The embarrassments attending coronal photography are enormously enhanced by the effulgence of daylight. Success here is more earnestly desired the less it can be hopefully anticipated; for the prospect is dim of realising Sir William Huggins's scheme of 1882, or any modification of it. It is true that, during the partial phases of the last couple of eclipses, sensitive plates were impressed by the inner corona, but it only showed as a vague glow throwing into relief the small segment of the moon outside the sun some forty seconds before and after totality.[2] Still, even this scanty measure of success was welcome as an earnest of what the incalculable future might bring. Everything depends upon catching differential effects—upon obtaining plates capable of *feeling* the delicate gradation between daylight pure and simple and daylight plus corona. And this would be greatly facilitated by acquaintance with the law of intensity in the coronal spectrum. It ought to be stronger in the upper reaches than the ordinary solar spectrum, since the corona escapes the heavy toll of blue absorption exacted from the photosphere by the "smoke-veil"; the question is, can this presumable superiority be rendered predominant enough for the ends of portraiture? The use of coloured screens, letting through the more refrangible rays,

[1] Wesley, *Knowledge*, Oct. 1900, p. 227.

[2] Maunder, *Knowledge*, vol. xxi. p. 109. Cf. the visual observations of Seagrave in 1900, *Astroph. Journ.* vol. xii. p. 99.

and barring out those lower ones in which mere glare has the advantage, has proved ineffectual; and the "double-slit method," so splendidly helpful in other departments of solar physics, has also been tried in vain.[1] In coronal photography, no bright line can serve the end in view because the gaseous spectrum belongs only to the inner corona, and the record aspired after is more especially of the outer corona, with its characteristic plumes, streamers, and aigrettes. Until the changes these undergo can be followed day by day, little will be satisfactorily known of their intimate relations with the different orders of solar phenomena, and still less of the underlying cause of variation.

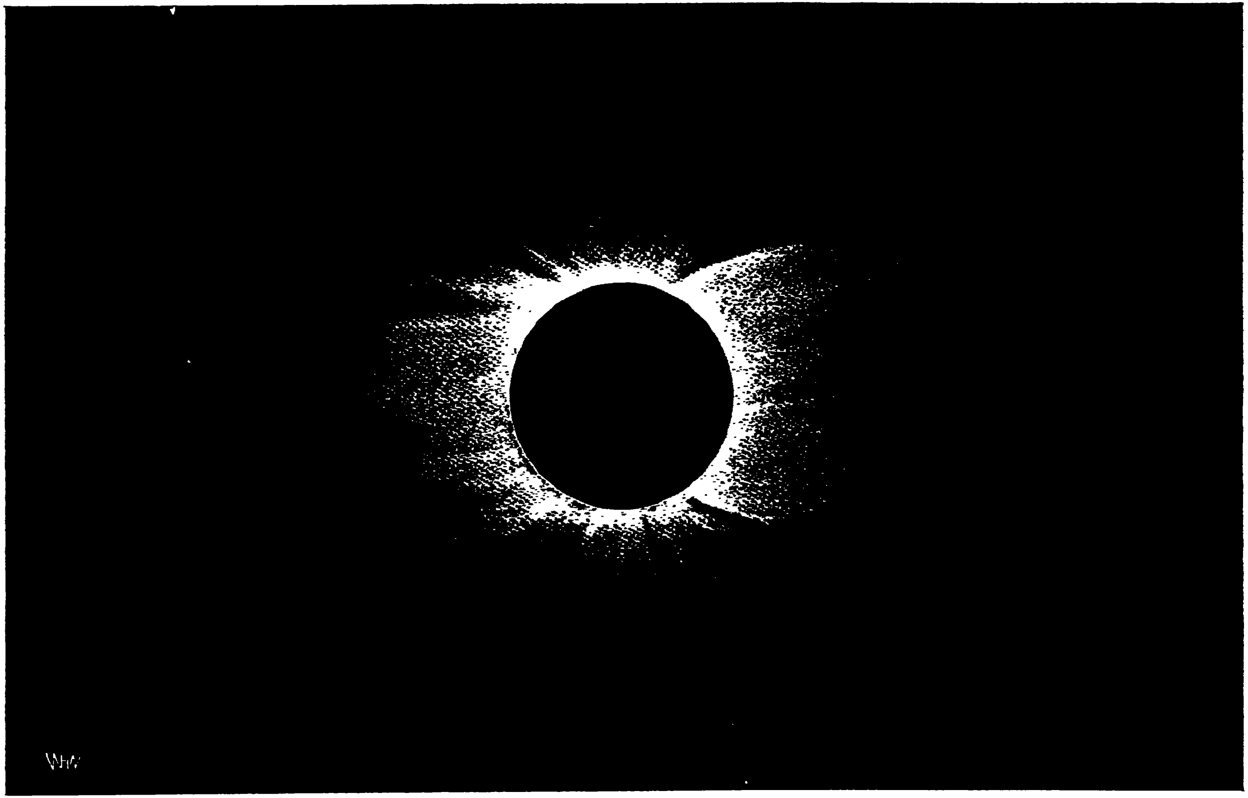
It has yet to be determined whether the corona rotates with the sun. Opposite motion-displacements above the east and west limbs, of the green line or one of its companions, would settle the point; but they show, if at all, most evasively. M. Deslandres first attempted such measurements at Fundium in West Africa, 16th April 1893.[2] He chose, however, as the object of his attack the K-line of calcium, since ascertained to be non-coronal, so that his results were null and void. Yet they marked a starting-point, for they sufficed to introduce the research definitively into the eclipse-programme; nor will it be dropped out of it, we may hope, until a substantial increase of knowledge has been gained. Subsequent experiments, although legitimately conducted, have been indecisive. Mr. Newall, in those tried by him at Pulgaon, 22nd January 1898, went too far afield for their materials.[3] He directed his spectroscope to points 8′—corresponding to upwards of 200,000 miles—from each limb, whence no bright line could be obtained, since they lay outside the limits of the gaseous corona. Professor Campbell,[4] on the other hand, found in spectrograms taken east and west of the sun during the same eclipse, a difference in position of the green ray giving an ostensible radial velocity of 3·1 kilometers per second, suggesting rotation at half that speed; but he regarded its genuineness as open to grave doubt.

[1] Hale, *Astr. and Astrophysics*, vol. xiii. p. 662.
[2] *Observations de l'Éclipse du 16th Avril 1893*, p. 43.
[3] *The Observatory*, vol. xxi. p. 188.
[4] *Astroph. Journ.* vol. x. p. 186.

PLATE VIII.

North.

East.




West.

South.

The Corona of 1900. Drawn by W. H. Wesley from Photographs taken by E. W. Maunder. (*Knowledge*, vol. xxiii. p. 227.)

More hopeful than the method of simple displacements is perhaps the method of *inclinations* recommended by Deslandres.[1] A small, intensely luminous image of the corona being thrown upon the slit of a powerful spectroscope, the varied deviations of the bright lines derived from its different parts should tell something as to the mode of motion prevalent throughout the appendage. If it rotates like a solid body, all in one piece, the velocity increases outward, and the lines would lie aslant on the plate in corresponding directions. If, however, the regimen be analogous to that governing Saturn's ring-system, in which every component particle revolves as an independent satellite, then the speed of coronal matter slackens with increase of distance from the sun, and the spectral rays emitted by it should be deflected the opposite way. The criterion, if it prove applicable, will be highly discriminative as regards rival hypotheses.

These may be classified as ejective, meteoric, and electromagnetic. Professor Schaeberle analyses the phenomenon into "streams of matter ejected from the lower latitudes of the sun."[2] To the materials of the longest rays he ascribes initial velocities up to 400 miles a second, and excursions outward to the remote neighbourhood of Jupiter or even Saturn; ogives and arches being due to eruptions of less violence; while the interplay of innumerable curving jets, foreshortened in all possible ways, explains the complex aspect of the sun's lucent crown. Mr. and Mrs. Maunder, again, consider the prominences to "represent centres of strong eruptive action, and that in consequence of such action coronal matter is driven upward from the sun over a very wide area in dome-like forms."[3] A succession of arches results, "the outer being less definite and complete than the inner ones. Outside all we find the curves defining the boundaries of the synclinal group."

There is much plausibility in these inferences. Prominences are visibly spouted or flung upward, and the lustrous filagree vaults often rising above them can scarcely have a totally dissimilar origin. But the whole secret is not thus laid bare. The rationale by eruptive action is no sooner

[1] *Loc. cit.* p. 50. [2] *Total Solar Eclipse, Dec. 1889*, p. 47.
[3] *The Indian Eclipse*, p. 121.

sought to be made exclusive than it meets contradictory facts. It offers no admissible explanation of varying coronal types; it ignores the mysterious coronium envelope; it seems to be negatived by the bolometric observations of Abbot in 1900; for obviously the light of the supposed bombs, projectiles, or pulverulent ejected streams should contain the ordinary solar proportion of heat-rays, which are nevertheless markedly deficient.

The corona, according to Sir William Huggins, must consist of "incandescent fog." And Professor Newcomb,[1] following a similar train of ideas, avers it to be made up of detached particles, wholly or imperfectly vaporised. They might be most sparsely distributed. Intense radiance would, he informs his readers, result from the occurrence of a single fragment of dust in every cubic mile of space about the sun. But how is the dust (if dust there be) supplied? Does it come from within or from without? Here the upholders of the meteoric theory join issue with the eruptionists. There must be rings and streams of meteors revolving quite close to the sun in orbits of all possible inclinations and considerably varied eccentricities. These furnish, we are told, the materials of the corona, which—as Dr. Scheiner has recently shown[2]—are raised to a temperature of incandescence by direct solar radiation. This view, nevertheless, like the eruption-hypothesis, is scarcely tenable in view of the non-thermal quality of coronal light.

There remains the electrical theory. Formally enounced by Sir William Huggins in 1885,[3] it remains unverified indeed, yet unrefuted. Coronal streamers are regarded by it as analogous to comets' tails; they issue forth under the influence of a repulsive force emanating from the sun; they are illuminated by electrical discharges due probably to differences of potential at their bases and extremities.[4] The magnetic relations of the phenomenon, vividly indicated by the minimum forms exemplified at the two eclipses of 1889, were ably discussed by Professor Bigelow.[5] He analysed

[1] *Popular Astronomy*, p. 260 (edit. of 1878).
[2] *Astroph. Journ.* vol. xii. p 25.
[3] *Proc. Royal Society*, vol. xxxix. p. 108.
[4] Deslandres, *loc. cit.* p. 62.
[5] *The Solar Corona discussed by Spherical Harmonics*, 1889.

coronal structure by spherical harmonics, on the supposition of its dependence upon some mode of action similar to that of free electricity, "the rays being lines of force, and the coronal matter being discharged from the body of the sun, or arranged and controlled" by a power proceeding from it. He further showed that the power was of a repulsive nature and varied inversely as the square of the distance;[1] but he avoided speaking of it as "electrical" out of "deference to the doubt that free electricity can exist at such high temperatures as prevail on the sun's surface," content to have proved "that some force is present acting on the corona according to the laws of electric potential."

The diagrammatic halo laid down on these principles was indeed the very "twin Dromio" of the corona of 1889; but they stood ill the test of prediction. The corona of 1893 failed to exhibit the special features anticipated for it by Professor Bigelow. Plainly the assertion that an illuminated magnetic field surrounds the sun, although scarcely deniable, does not comprise the whole truth. The same may be said of Hermann Ebert's "electro-magnetic theory."[2] He defines the corona as "the visible reaction of the finely-divided matter in the vicinity of the sun upon the dielectric polarisation proceeding from the different parts of the sun." Luminosity is evoked by Hertzian oscillations propagated outward with the velocity of light, and its filamentous texture corresponds to differences in dielectric stress connected with the distribution of electricity on the sun's surface.

The auroral aspect of the corona has often been commented upon. M. Ebert remarks[3] that the magnetic lines of force near the earth are not more definitely traced out by the play of polar lights than are those about the sun by the disposition of coronal rays. The truth of this, however, is patent only as regards aureolas of the minimum type. In those visible at maximum it is at any rate disguised. For, as the sun's internal activity augments, beamy outflows predominate over tufted effluences, although both kinds of radiance may be simultaneously present. Professor Holden considered the sun

[1] *Public. Pacific Society*, vol. iii. p. 216.
[2] *Astr. and Astrophysics*, vol. xii. p. 804.
[3] *Magnetic Fields of Force*, p. 73 (1897).

to be *hairy* all over, and not merely at the poles. "There is no latitude," he wrote, "at which we can say that here the polar rays end and a new species—equatorial rays—begins."[1] This was also recognised by M. Hansky in his study of the corona of 1896;[2] but the superposed streamers and arches can with difficulty be included in any magnetic theory. On the other hand, Mr. Pupin of Columbia College obtained in 1892 striking imitations of the maximum type of corona by means of electrical discharges through partially exhausted bulbs.[3] Effects of polarity being, however, wholly absent, the reproduction failed to convey one fundamental characteristic of the real phenomenon. But the deficiency was supplied, three years later, by Ebert's experiment of subjecting "coronoidal" tubes to the action of a powerful magnetic field. The organising effect upon the light-effluence was just what was needed, according to Bigelow's contention, to give nature's own imprimatur to his "magnetic theory of the solar corona."[4]

A fact of high import in this connection is that the coronal bright lines are not reversed in the Fraunhofer spectrum. Coronium, and the gases associated with it, exercise no perceptible absorption upon the light transmitted through them. Now this kind of inertness, according to M. Cantor's experiments,[5] is distinctive of substances glowing by electrical stimulation, so that we have here—as the late Professor Fitzgerald pointed out—a confirmation, absolutely *sui generis*, of the conjecture that coronal emissions are analogous to those of an illuminated vacuum-tube.

Yet none of the views propounded on the subject are completely satisfactory. They have points of contact with truth, but they do not closely embrace it. This, indeed, could hardly be expected at so comparatively early a stage of coronal research. For the questions involved are beyond measure baffling and intricate. We may re-enumerate them.

One that is fundamental relates to coronal heat. Its virtual absence, attested bolometrically at Wadesborough in

[1] *Reports on Eclipse of 1st January, 1889*, p. 10.
[2] *Bull. de l'Acad. des Sciences de St. Pétersbourg*, t. vi. March 1897.
[3] *Astr. and Astrophysics*, vol. xi. p. 483.
[4] *Amer. Journ. of Science*, vol. xi. p. 253, 1901.
[5] *Annalen der Physik*, 1900, p. 462; quoted by G. F. Fitzgerald, *Nature*, vol. lxii. p. 7.

1900, must be confirmed during future eclipses before Deslandres's contrary inference[1] as to the copious presence of long waves in coronal light can be finally dismissed.

The coronium-envelope offers a problem which stands almost apart from that of the stellate appendage surrounding it. And it is one that can scarcely yet be grappled with. No familiar substance enters into its composition. Its ingredients are altogether exotic. They do not diffuse into the chromosphere, while those of the chromosphere are as strictly excluded from the corona. The cause of this extraordinary circumstance will perhaps long remain obscure. Meanwhile, through the attempted apportionment of the coronal rays photographed in totalities between sundry hypothetical substances we are led to regard coronium as only one of a group of gases foreign to terrestrial experience.

The rotation of the corona can be measured only by the most refined methods; but there is little doubt that they will be successfully applied. Movements of other kinds may also be spectroscopically determined, since they are likely, in many cases, to take directions oblique to the limb, and therefore to have large components along the line of sight to the earth. Notwithstanding the lasting, and, in some respects, the growing importance of securing the best possible picture-photographs of the corona during totalities, novel revelations are scarcely to be expected from them. Their leading interest just now centres, first in the structural relationship of coronal arches with prominences, next, in the information they may afford about dark markings in the solar appendages. For the rest, we must look to daylight photography. When the great desideratum is attained of getting behind (as it were) the veil of atmospheric glare, we shall be able to trace the progress of coronal change, to follow the unbuilding and rebuilding of the typical aureolas, to witness, perhaps, sudden coronal developments in sympathy with chromospheric outbursts. From the vantage-ground thus gained, in short, the true function of the corona in the solar economy can be systematically investigated. During the few crowded moments of eclipse this is not possible.

[1] *Comptes Rendus*, t. cxxx. p. 1691; *Nature*, 5th July 1900.

# CHAPTER XII.

## THE SUN'S ROTATION.

THE mode of the sun's rotation is perhaps the most significant feature of his constitution. A thorough understanding of it would doubtless bring with it an explanation of many other outstanding difficulties. But it seems, unfortunately, a long way off. No more has been attained as yet than the representation of the observed facts by empirical formulæ. That is to say, a law of order has been discerned in them although their cause remains obscure.

No single period of rotation can be ascribed to the sun. Each element of the photosphere, probably each layer of the chromosphere, moves round the axis in a fashion of its own. The fundamental rate, if such there be, is so masked by local drifts as to be unrecognisable. The most hopeful road to its eventual detection seems to be by the gradual disentanglement of the solar influences affecting terrestrial magnetic phenomena. The immediate task in hand, however, consists in extending and giving precision to knowledge on the whole subject, in bringing varied methods to bear upon it, and in linking into some kind of sequence the circumstances ascertained.

Until spectroscopic and photographic means became fully available, the solar rotation could be determined only by timing the circuits of spots. And spots were very soon found to have "proper motions" precluding them from discharging the function of points of reference. Hence there could be no unanimity as to the sun's rotation, the period arrived at by each observer depending upon his choice of spots. At length Carrington's scrutiny during the years 1853 to 1861 showed

the systematic nature of these baffling diversities. They proved to vary with heliocentric latitude, and the great solar *swirl* was brought into evidence. Once in about twenty-five days the visible surface of the sun sweeps round at the equator; but as the distance from it increases, the time lengthens progressively. The rate of retardation is given mathematically in the following expressions, which, being artificially adjusted to correspond with observation, might be multiplied and modified indefinitely:—

FORMULÆ OF SOLAR ROTATION.

$X = 865' - 165' \sin \frac{7}{4}\, l$ (Carrington).
$X = 1011' - 203' \sin (41° \; 13' + l)$ (Spœrer).
$X = 862' - 186' \sin^2 l$ (Faye).
$X = 858' - 157' \sin^2 l$ (Tisserand),
X signifying the daily angular motion, $l$ the solar latitude.

Formulæ of the kind, moreover, are of restricted application. Based exclusively upon spot-measurements, they can scarcely be trusted outside of the spot-zones—that is, beyond 38° north and south of the equator. Carrington's gives a period of $25^d\ 9^h\ 53^m$ where $l = 14°$, of $26^d\ 9^h\ 9^m$ for $l = 30°$; and he adopted as the standard period $25^d\ 9^h\ 0^m$, conformed to in latitude $13\frac{1}{2}°$. But what this average speed of transport actually represents, is the mean rate of motion of the multitude of sun-spots,[1] not the rotation of the body of the sun. Professor Bigelow argues from meteorological analogies that this prevails without disguise at the equator, while retrogressive currents of a "trade-wind" character lengthen the periods derived from observations in the spot-zones.[2] But such-like comparisons are plainly inadmissible. More plausible, although far from decisive, is his contention that the equatorial period must be the true one because it lends itself to the correlation of terrestrial phenomena—auroræ, magnetic storms, wind and weather changes—with solar outbreaks.

Solar rotational studies entered upon a new phase with

[1] Bigelow, *Astr. and Astrophysics*, vol. xii. p. 823.
[2] *Astr. and Astrophysics*, vol. xii. p. 825.

the application to them of the spectroscope. The particular importance of the innovation lay in the change of venue which it involved. A new court, so to speak, was constituted, a fresh set of witnesses called. These were the Fraunhofer lines; and while requiring more delicate treatment, they seemed likely to prove more trustworthy than their predecessors. Spots do not float inertly on the photospheric tide. They are subject to individual hurryings and laggings that to some extent invalidate the record of their axial progress. Fraunhofer lines, on the contrary, are eminently steadfast. They fall short, it is true, of the absolute fixity formerly ascribed to them; yet after every deduction has been made, their reputation as natural constants remains substantially intact. It must, however, be borne in mind that what the Fraunhofer lines tell about the sun's rotation is not strictly comparable with the information derived from spots. For they proceed from a different level, and may therefore obey a different law of revolution. They indicate the velocity, not of the sun itself, but of the absorbent strata in which they originate.

The eastern limb of the sun advances, the western limb recedes at the rate of 1·2 miles a second. The consequent line-displacements amount to just $\frac{1}{150}$ the little gap between the D-lines of sodium. In 1871 their simple detection by Vogel was a feat of some moment.[1] Five years later, Young was enabled, by his early possession of a grating or diffraction spectroscope, to fix their range with approximate accuracy. Then Langley showed how, by their means, to distinguish at a glance lines of solar and telluric production. For in juxtaposed spectra from opposite ends of the equator, the solar lines, being affected by rotation, are manifestly "notched," while atmospheric rays run straight on without a break. They stand self-announced as of domestic production.

The differential plan of measurement thus suggested obviates many forms of otherwise inevitable error. It was adopted by Dunér in his classic work on the sun's rotation, presented to the Royal Society of Upsala 14th February 1891. He selected two iron lines in the red (λλ 6301·72, 6302·72) for comparison with a pair of adjacent oxygen lines from the "Alpha" band, known to be terrestrial, and there-

[1] *History of Astronomy* (A. M. Clerke), 4th edit. p. 202.

fore exempt from motion-shiftings.[1] They were then safely treated as fiducial; and the intervals between them and the solar lines differed, east and west of the equator, to an extent corresponding with rotation in a period of twenty-five and a half days. By the use of the utmost refinements, the observations were carried up to within fifteen degrees of either pole, where the period was found to be protracted to thirty-eight and a half days, the intervening zones showing intermediate velocities. Direct acquaintance with the sun's axial movement was thus extended far beyond the regions of spot-occurrence; and only direct acquaintance is, in this matter, of any avail, since the formulæ devised to suit low latitudes break down nearer the poles, disclosing their unsoundness by a total want of agreement in the periods calculated from them.

"Carrington's law" might have been true of spots only; it might have denoted some peculiarity in their mode of production, causing a systematic increase of backward drift, north and south of the equator. The Upsala measures, however, proved it to apply, irrespectively of spots, to the solar globe generally. They told, indeed, something more than this. The period deduced from them was longer than that given by spots. The difference amounted to about half a day, and it persisted in all latitudes—that is to say, the vapour of iron surmounting the photosphere gyrates more slowly than the spots *in* the photosphere. A variation of angular speed with elevation above the sun's surface was for the first time indicated. Confirmatory evidence was soon forthcoming.

The photographic investigation of facular movements was attempted by Dr. Wilsing at Potsdam in 1888.[2] From 1012 measurements executed upon 108 plates, he obtained a constant angular velocity of 14°·27 per diem, equivalent to a period of 25·23 days, which is just that of spots situated ten degrees from the equator. But the conclusion that faculæ in all parts of the sun conform to it was certainly fallacious. M. Bélopolsky made this apparent in 1892,[3] and M. Stratonoff of Taschkent still more decisively in 1894-96.[4] His research

[1] *Recherches sur la Rotation du Soleil*, p. 55.
[2] *Potsdam Publ.* Bd. iv. pt. ii.; *Astr. Nach.* Nos. 3000, 3153, 3287.
[3] *Astr. and Astrophysics*, vol. xii. p. 632.
[4] *Astr. Nach.* Nos. 3275, 3344.

included the determination of 2158 positions of 997 faculæ on 316 Pulkowa plates, and furnished the clearest evidence of their poleward retardation. The Stonyhurst drawings, discussed by Fathers Sidgreaves and Cortie,[1] yielded similar results. Concomitant increase of period and latitude is, in fact, a rule without exception on the sun.

Faculæ, however, have a mean rate of their own. In the same parallels they are transported more rapidly than either spots or absorbent vapours. Their period of rotation is the shortest attributable to any solar formations. The main facts of the case can be taken in by a glance at the following little table:—

PERIODS IN DAYS

| Heliographic Latitude. | Faculæ. | Spots. | Reversing Layer. |
|---|---|---|---|
| 0° | 24·66 | 25·09 | 25·46 |
| 15° | 25·26 | 25·44 | 27·49 |
| 30° | 25·48 | 25·81 | 31·83 |

The equatorial facular period, it is worth noting, is nearly identical with that ascribed by Hornstein, on the ground of magnetic observations, to the mass of the sun.

The diversities exhibited above are as perplexing as they were unexpected. They do not even fall readily into any satisfactory order of progression. The slowest movement belongs to the reversing layer, or at least to the slice of it stopping out Dunér's iron lines; for there is no certainty that the entire stratum rotates unanimously. It *is*, however, certain that it covers both spots and faculæ. The level of absorption is higher than the level of the photosphere with all its immediate appendages. This fact has been already insisted upon;[2] it may perhaps usefully be reasserted in the present connection. Fraunhofer-absorption is stamped in the prismatic rays of faculæ and sun-spots precisely as in those of the photosphere. They have then been demonstrably sifted through the same screen of incandescent vapours. We have

[1] *Monthly Notices*, vol. lv. No. 1; *Astroph. Journ.* vol. xiv. p. 317.

[2] See *ante*, p. 98.

yet to learn that they escape any minutest part of the absorptive effects produced in ordinary sunlight. They must accordingly be submerged beneath the whole series of strata occasioning them. At the same time, it has to be borne in mind that Dunér's deductions rest upon a narrow basis. He measured only a single pair of lines, and we lack the specific assurance that those individual lines occur in the facular and spot spectra. Presumably they do; no reason is apparent why they should behave exceptionally; but a direct record of their actual presence would be satisfactory. They should also be looked for in the "flash" at the edge of the eclipsed sun. Their detection as brilliant lines would confirm and settle their status.

But here we encounter an anomaly. Since the reversing layer rotates more slowly, and lies higher than the photospheric formations, a law of retardation with altitude might be assumed. Its prevalence is, nevertheless, contradicted by the relations of spots and faculæ. Faculæ undeniably rise above spots, yet they wheel more rapidly; they give a shorter period. This seems to be established by Wolfer's[1] confirmation of Stratonoff's results. Thus while retardation outward is indicated by the reversing layer, acceleration outward is forcibly suggested by faculæ. And there is a general consensus of opinion that this rule applies generally, so that the comparative tardiness of the absorptive region stands over as an unexplained discrepancy. Even within the region itself, Mr. Lewis E. Jewell has found indications of diminishing angular velocity towards the photosphere, where also the equatorial quickening is small compared to its value higher up.[2] Moreover, Bélopolsky's speculations as to the nature of the corona, which probably adumbrate, if they do not convey truths, require that it should rotate much more swiftly than the sun itself.[3] The forecast will doubtless be tested ere long by eclipse-spectrograms. Indeed, further evidence is much needed on a number of crucial points connected with the sun's rotation.

Dunér confessed his inability to imagine a "Why" for the singular rotatory régime of which he had clearly expounded

[1] *Vierteljahrsschrift Naturforsch. Ges. in Zürich*, Bd. xli. 1896.

[2] *Astroph. Journ.* vol. iv. p. 138.

[3] *Bull. de l'Acad. de St. Pétersbourg*, t. vi. No. 3, p. 293.

the "How." "It constitutes," he remarked, "one of the most difficult problems in astrophysics." One theory after another has been proposed, and sunk out of sight, overweighted by manifest inconsistencies. A machine "going" like the sun the wit of man has not yet been able to devise. Nevertheless, a means of evading the difficulty has been found. The possibility has been perceived, and perhaps too readily admitted, of regarding it as a legacy from chaos to cosmos. The embarrassments surrounding the subject may be relegated to a far-distant age, and to a state of things for which the investigators of to-day disclaim responsibility. The anomaly, on this view, is a survival of nebulous conditions, which, so far from having a present sustaining cause, is, and has always been, subject to the destructive agency of friction. Why then, it may be asked, has it persisted throughout the æons of the sun's growth? Should it not have been quite early abolished, if it be nothing more than a residual inequality, begun to be smoothed away in the dim foretime when the solar globe took shape? Mathematicians reply in the negative. Wilczynski of Berlin gave in 1896 an apparent demonstration that internal resistance cannot change the diurnal arc described by any point on the sun to the extent of two minutes in twenty-seven million years.[1] But Harzer showed it to be applicable only to cases non-existent in nature.[2] It would be valid under ideal circumstances; things being as they actually are, it falls to the ground.

Starting from less questionable premisses, however, Wilsing of Potsdam in 1891,[3] and Sampson of Durham in 1894,[4] reached practically the same conclusion. They agreed that millions of years must elapse before the sun comes to rotate "all of a piece," like a solid body. There is, indeed, one flaw in their reasoning. Both limit convective circulation within the solar globe to a relatively thin shell of material. They assign to radiation an essentially superficial character. In the attempt to prove that the rotational currents flow without impulsion, they sacrifice the functional efficiency of our great light-giver. For assuredly its immense output of radiant energy

[1] *Astr. Journ.* No. 416; *Astroph. Journ.* vol. iv. p. 101. [2] *Ibid.* vol. v. p. 37.
[3] *Astr. Nach.* No. 3039; *Astroph. Journ.* vol. iii. p. 247.
[4] *Memoirs Royal Astr. Society*, vol. li. p. 123.

can only be supplied from interior stores, rendered available by powerful and *deeply rooted* vertical currents. But the continued activity of such a system should speedily efface inequalities of surface drift, unless some countervailing force maintained them.

Dr. Wilsing asserts that, in the comparatively late "phase of celestial evolution represented by the fixed stars, radial currents are beginning to disappear." It might more plausibly be argued, considering the intense brilliancy of such bodies, that radial currents are in them at a maximum of strength and volume. "We are therefore relieved," the author continues, "from the difficulty of accounting for 'Carrington's law of rotation' on mechanical and physical principles, since it appears as the result of earlier conditions of motion."[1]

We leave a good deal to the coming time; why should we not shift an occasional perplexity back to the broad shoulders of antiquity? Much that is inconceivable in a sun might be possible in a spiral nebula. No such expedient, however, will answer the present purpose. The originating cause of the sun's rotational anomalies, whatever it may have been, continues to act. In a globe so profoundly disturbed, they could not possibly have survived of themselves.

Professor Young finds the necessary driving power in falls of cooled materials, bringing with them to the photosphere the swifter motion appertaining to a wider circumference. The consequent accelerative impulse would be greatest at the equator, and would diminish to nothing at the poles, according, so far, with the observed facts. Spots, moreover, by onrushes at epochs of reconstruction or recrudescence, formally acknowledge the receipt of supplies from above. But Carrington's "law" governs all the solar formations, and the rationale by continuous downward precipitations seems to be of very partial applicability. Faye tried to solve the problem on an inverse principle. Instead of descents from without, he postulated ascents from within, the equatorial retardation being less than that in high latitudes because the rising matter comes from nearer the surface. This, however, was a purely artificial arrangement, with no voucher for its reality. The explanation needed to be explained. Speculation here, as elsewhere, must await the progress of direct inquiry.

[1] *Astroph. Journ.* vol. iii. p. 248.

# CHAPTER XIII.

## THE SOLAR CYCLE.

SOLAR periodicity is a most complex phenomenon. The more it is studied, the less it seems to be understood. Its effects branch out into endless entangled and obscure *fibres* of fact, to trace all of which back to their root-source would be an almost superhuman task. At present they can only be dealt with in groups and tentatively. Their subtle, and often disguised relationships need much patience for unravelment. They need, above all, a free mind. Prepossessions are sure to compromise truth.

The sun is subject to a rhythmical tide of disturbance, ebbing and flowing in about eleven years. But the flow is irregular and spasmodic. Both the intensity of the crises and the intervals at which they recur vary largely and unaccountably. Probably the eleven-year cycle is involved in others. One, there is reason to believe, brings about alternate accentuations and partial effacements of change comprised within a term of some sixty-five years.[1] And minor pulsations—wavelets on the great rollers—are besides evident. Prediction, nevertheless, remains at fault. Spot-maxima are delayed or anticipated, they are languid or energetic, as the outcome of modes of action defying calculation. Not even the loose fetters of an arbitrary formula have ever been forged for them. The attempt would indeed be hopeless, since the laws governing them, besides being highly intricate in themselves, are plainly disturbed in their working. Circumstances intervene which we must call "accidental." Could we describe them in detail the science of solar physics would lie before us as an open book.

[1] Cf. Halm, *Annals Edin. Observatory*, vol. i. p. 99, 1902.

The "error" of the spot-period may amount to nearly half its normal length. Thus sixteen years elapsed between the maximum of 1788 and the next certainly ensuing, and only 7·3 years separated the culminating points in 1829·9 and 1837·2. A characteristic feature of the representative curve is that it mounts more rapidly than it descends. Maxima succeed minima, on an average, after 4·5 years, while the corresponding minima are only reached after 6·1 years. Substantially, a disparity of this kind is probably always present, although now and again masked by the prominence of a secondary maximum. These peculiarities deserve the most careful attention, as sufficing in themselves to place the sun in the category of variable stars. His spot-curve might almost be said to be modelled on the light-curves of such objects; and the analogy is eminently instructive. We learn from it, for instance, that a spotted condition in the sun matches a phase of strong luminosity in the stars; and are hence led to infer that the sun radiates most powerfully when his disc is most maculated. The extreme difficulty of obtaining direct proof of this relation lends especial value to the side-wind of evidence thus brought to bear.

Now an increase of radiation involves a quickening of the sun's internal circulation; and the process, when hurried, is likely to become tumultuous. So that a connection is easily traceable between heightened brilliancy and photospheric laceration. Spots, however, are only the most conspicuous symptoms of an agitated state. Faculæ and prominences follow suit. They are indeed too intimately bound up with spot-economy to do otherwise. The corona, by a less obvious necessity, sympathises, and the periodicity of all these formations has a double aspect. They fluctuate in mode of distribution as well as in vigour of development. Spots, faculæ, prominences, and corona, all vary similarly and simultaneously in heliographic latitude as the waves of disturbance rise and fall. The spot-zones are not stationary. They shift over the body of the sun according to a definite law enounced by Carrington in 1859, and confirmed by Spoerer in 1861.[1] At maxima they occupy mean positions

[1] Clerke, *Hist. of Astr.* pp. 148, 149, 4th ed.; Spoerer, *Potsdam Publ.* Bd. x. part i. 1894.

in about fifteen degrees of north and south latitude; then, as the cycle advances, they close together, and the commotion finally dies out near the equator. Meanwhile, the start of a new series in high latitudes has anticipated the termination of the old. Feeble at the commencement, it gains strength as it departs more and more from its native regions. "Mobilitate viget, viresque acquirit eundo." Fig. 17, copied from a diagram of Spoerer's, illustrates the nature of this progression. The overlapping of the curves at minimum brings before us the remarkable circumstance that, as a consequence of successive disturbances breaking out before those antecedent to them have expired, the full duration of each is, not eleven, but twelve to fourteen years. Moreover, spot-

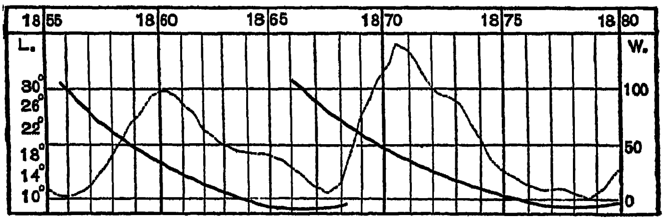



FIG. 17.—Spoerer's Curves of Sun-spot Latitude (from *The Sun*, by C. A. Young).

production at minima, however inactive, has a twofold nidus; two widely separated zones in each hemisphere are appropriated to it. A further characteristic of the cyclical decline in latitude is that it proceeds in "waves." "Every fourth or fifth rotation," Mr. Maunder tells us, "there will be an effort to reach a higher level, a lift of one or two degrees, and then a gradual slipping back until a fresh effort brings another small lift, but a weaker one than the last. And so the cycle goes on; the decline is continual on the whole, but is broken and interrupted by these frequent little struggles to get back to a higher plane."[1] The growth in spotted area accompanying the descent of the zones is similarly rhythmical. So closely connected, indeed, are these two modes of periodicity that irregularities in the cyclical progression frequently show under the double aspect of abnormal outbreaks of spots, and abnormal movements in

[1] *Knowledge*, vol. xv. p. 131.

latitude. Theories are accordingly valueless that fail to rationalise simultaneously both kinds of facts. Several, indeed, profess to do so, but by constrained expedients.

The zonal law applies, with qualifications, to faculæ and prominences. Eruptive prominences are strictly governed by it. They frequent the spot-belts, it may be said, exclusively. The quiescent kind, on the contrary, avoid them,[1] and have their main gathering-grounds within fifteen degrees of either pole.[2] They may even occur, near spot-maxima, right up to 90° of latitude. As activity decreases, however, they too move downward, and crowd more or less closely towards the equator, although maintaining at all times a wider range than spots. Faculæ show a divided allegiance. They attend on spots, and their principal maxima are hence displaced with the spot-zones, while their affinity with quiet prominences is evinced by the occurrence of secondary maxima in high latitudes. Not that their local arrangement is the same with that of prominences.[3] Discrepancies are frequently noted; and they are important as indications that the two varieties of outgrowth do not originate under identical conditions.

The succession of coronal types is in clear accord with the law of zones. Streamers and prominences march, on the whole, closely together. They unanimously quit the poles after each maximum; they linger in company over middle latitudes, where "synclinals" overarch red flames at epochs of medium activity; finally, they descend towards the equator, the white wings of the minimum corona meeting and spreading above the last members of each decadent eruptive series.

The spectral periodicity of the sun is less marked than might have been expected. It is, indeed, almost confined to spots. The ordinary spot-spectrum at minimum (to repeat what has been already stated) includes many broadened iron lines, replaced at maximum by vanadium and scandium absorption. The nature of the individual spot, however (as we have seen), not the stage of the cycle, is really the determining cause of this diversity, which recurs periodically,

[1] Fényi, *Publ. Haynald Observ.* Bd. vi. p. 41.

[2] Mascari, *Astroph. Journ.* vol. ii. p. 119; Evershed, *Astr. and Astroph.* vol. xi. p. 426.

[3] Mascari, *Astroph. Journ.* vol. vi. p. 371.

simply because minimum-formations are usually of the tranquil sort. The chromospheric spectrum has quite other relations. It does not vary fundamentally; but the metallic rays temporarily added to it become fewer as metallic injections fall off. Nor is the quality of coronal light subject to radical change. Only the relative strength of its constituents slightly fluctuates. In the "winged" type the gaseous emissions are feebler than in the "radiated" type; yet they are always present and always the same.

The virtual invariability of the Fraunhofer spectrum is more surprising, since the reversing strata are in immediate contact with the periodically agitated photosphere. They preserve, nevertheless, an almost inviolable tranquillity, and their composition remains unaltered from one cycle's end to the next. A single recurrent modification is, however, just traceable. It is that produced by the emergence, at maximum, of the facular bright lines H and K. *Pro tanto* and *pro tempore*, the symptom constitutes the sun a "bright line star." Analogous detections in stellar spectra would afford a possibility of determining the spot-periods of globes in the solar condition; but they are, for the present, scarcely to be hoped for. The observation is difficult in the sun; in a star, unless facilitated by extraordinary facular development, it would be impossible.

The throbbings of solar agitation affect his entire system. In how many ways, and by what hidden means, we can but vaguely surmise. Terrestrial meteorology, as a whole, is certainly embraced in the great cycle, although the details of its conformity baffle, by their intricacy, the most painstaking pursuit. Only in the magnetic department there is no room for doubt. A thoroughly satisfactory discussion of the subject was completed in 1898-99 by Mr. William Ellis,[1] who for long years controlled this branch of work at Greenwich. Comparing the observations of the diurnal range of magnetic declination and horizontal force made at the Royal Observatory during the years 1841 to 1896, with the sun-spot numbers for the same interval determined by Wolf of Zürich, he found between the two orders of phenomenon, not only a general parallelism, but a correspondence in

[1] *Proc. Royal Society*, vol. lxiii. p. 64; *Monthly Notices*, vol. lx. p. 142.

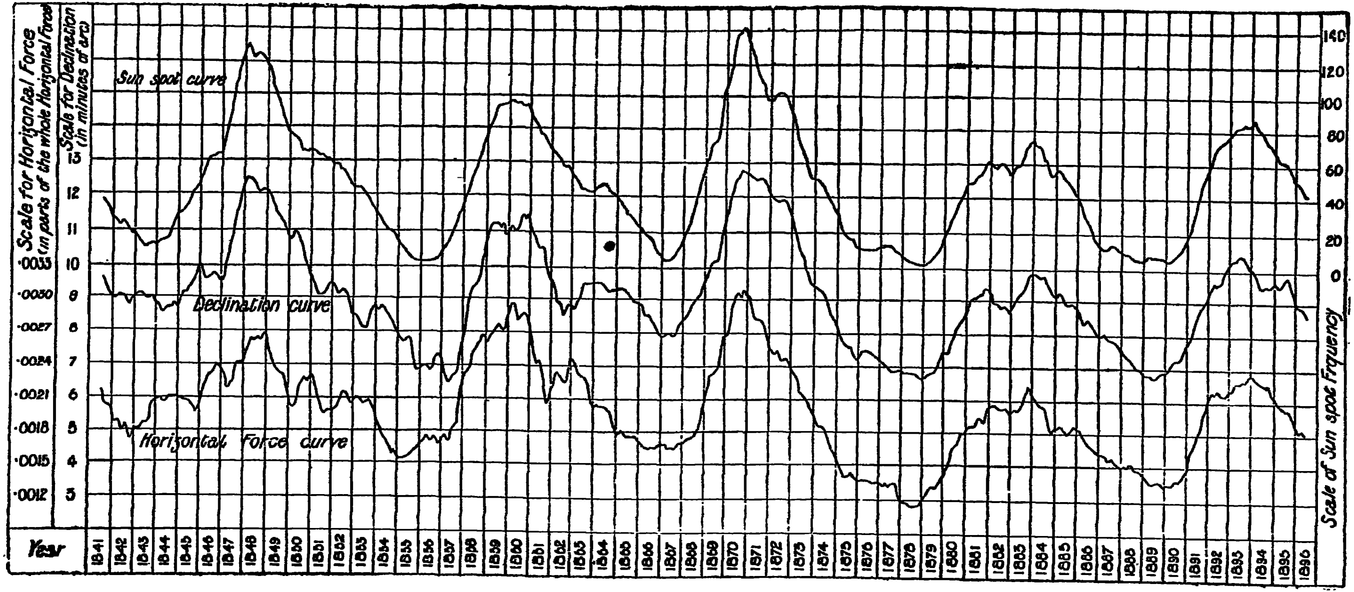



FIG. 18.—Curves of Sun-spot Frequency and Magnetic Agitation (Ellis).

irregularities of period and secondary variations of intensity. This is strikingly evident in Fig. 18, copied by kind permission from his paper read before the Royal Society, 10th March 1898.

The sympathetic relation extends to auroræ. They even obey a "law of zones" similar to that regulating the distribution of sun-spots. The earth is circled—presumably in each hemisphere—by an auroral belt, which advances into temperate latitudes at epochs of cosmic disturbance, but retires towards the pole as it quiets down. The reality of the connection was singularly affirmed by the simultaneous dearth of sun-spots and auroræ during the seventeenth century. A prolonged solar calm appears to have set in about 1643. Galileo and Scheiner had been at no loss for objects of study; but the diligence of their successors, although unrelaxed, went mostly unrequited. To Cassini, Flamsteed, Hooke, De la Hire, the occurrence of a spot was an event of rare interest, which rewarded perhaps a decade of fruitless watching. Yet, as Mr. Maunder says,[1] the cycle was "submerged" rather than actually abolished, "the crests of a sunken spot curve" being marked by the solitary spots perceived in 1660, 1671, 1684, 1695, and 1705. Definitively, the protracted minimum came to an end in 1716, and there was a normal maximum in 1718. Meantime auroræ too were in abeyance.[2] None were seen in England from 1575 to 1706, when a glimmer of polar lights heralded the magnificent display witnessed by Halley, 17th March 1716. That there was concomitant magnetic quiescence need not be doubted; but Gauss of Göttingen was still in the distant future, and nothing could be known on the subject.

Individual outbreaks on the sun are often unmistakably associated with commotions of the terrestrial magnetic system. These so-called "storms" are world-wide in their nature, abrupt in their origin, and bear witness to some sudden *vital* spasm attacking the globe as a whole, and at once. Auroras and earth-currents make part of these mysterious affections, which commonly reach their height when a large spot-group is nearly central on the disc—that is to say, when it is broadside on to the earth. Instances abound. On 17th

[1] *Knowledge*, vol. xvii. p. 175. [2] *Ibid.* p. 206 (A. M. Clerke).

November 1882, the photosphere was, to the naked eye, conspicuously rent. The coincident aurora and magnetic storm were said to "beggar description." [1] A spindle-shaped beam, which darted that night across the sky, was indeed a unique phenomenon, and, on its farthing-candle scale, recalled the amazing solar flambeau of 1st September 1859. Nor can the contemporaneous twitchings of the Kew magnets on this latter occasion be regarded as accidental, any more than the sudden small disturbance of all three magnetic elements which accompanied an outburst of faculous light on 17th June 1891.[2] The magnetic turmoil raised by the transit of the enormous spot of February 1892 was exceptionally violent. Earth-currents seriously interfered with telephonic and telegraphic communication in all parts of our busy world; [3] the needles at Greenwich went completely off the prepared track of photographic registration; [4] and an auroral pageant completed the programme of response. Similar concurrences were observed in February 1894, September 1896, and March 1898, to mention a few out of a multitude of cases. Yet the sympathetic connection is not invariably manifest. A hole in the sun may evoke no earth-trouble. Mr. Maunder hence concludes that "though sun-spots are the particular solar phenomenon most easily observed, we must not therefore infer that their number and extent afford the truest indication of the changes in the solar activity which produce the perturbations we remark in our magnetic needles." [5]

Not the spot itself, but the connascent agitation thrills the terrestrial organism. Quiet formations pass unheeded; crises of growth or reconstruction meet with instant rejoinders. Tacchini [6] accordingly holds that *chromospheric*, not *photospheric* phenomena are, in this respect, truly influential, and that it is to the fierce flame-rushes above spots that the magnetic nerve-system is sensitive. The view is favoured with some hesitancy by Professor Hale.[7] Professor Bigelow, as the result of much suggestive inquiry, affirms that "from

[1] *Trans. Astr. Society of Toronto*, 1897, p. 80.
[2] *Observatory*, vol. xiv. p. 328. [3] *Ibid.* vol. xv. p. 143.
[4] Maunder, *Knowledge*, vol. xv. p. 89. [5] *Ibid.* p. 93.
[6] *Astr. and Astrophysics*, vol. xi. p. 437. [7] *Ibid.* p. 925.

the sun to the earth come two great supplies of energy, both types of radiation through the ether"—one propagated by plane waves, the other by vortical rotation—"and possessing very different properties, the one visible to the eye, the other visible to magnetic perceivers." And he computes, from various indications, a value for the normal magnetism of the sun about one-fifth the maximum of steel, which may, at epochs of extraordinary disturbance, be augmented fifty-fold.[1]

Variations in the sun's electrical state assuredly accompany his more obvious cyclical changes. "May not," Dr. Schuster asks,[2] "the periodicity of sun-spots and the connection between two such dissimilar phenomena as spots on the sun and magnetic disturbances on the earth, be due to a periodically recurring increase in the electric conductivity of the parts of space surrounding the sun?"

The surmised alteration may be a consequence, it can hardly be the cause of solar periodicity. Its actual occurrence, however, is far from unlikely. Certain cometary phenomena lend it a qualified support. The grouping together near sun-spot maxima and minima respectively, of the bright and faint apparitions of Encke's comet during a century (1786-1885), forced itself upon M. Berberich's attention in 1888.[3] Correspondences of this unexpected form were even traceable with displaced epochs of activity, such as the retarded maximum of 1788, and the premature maximum of 1837. Some indications were besides gathered that comet-discoveries become more numerous as the tide of solar energy rises, many that would otherwise pass unseen being lifted into visibility by accesses of transmitted excitement. But this relation, M. Berberich admitted, might be more apparent than real.

One still more recondite and unaccountable has been lately adverted to by Mr. J. Halm.[4] He contends that the physical condition of the sun reacts perceptibly on the motion of the earth. Variations in its orbital elements, which have hitherto baffled attempts at explanation on gravitational principles, are comprised, he finds, within the "great" spot period of about

[1] *Astr. and Astrophysics*, vol. xii. p. 717. [2] *Report Brit. Ass.* 1892, p. 634.
[3] *Astr. Nach.* Nos. 2836, 2837.
[4] *Nature*, vol. lxi. p. 445; vol. lxii. p. 460; *Astr. Nach.* No. 3619.

sixty-five years. The obliquity of the ecliptic, for instance, instead of decreasing uniformly with the time, shows subordinate fluctuations synchronising with the long waves of solar activity. Its shorter waves, on the other hand, prove to be influential upon the variation of latitude. Mr. Halm considers that the deviations of the terrestrial pole conform unmistakably to the eleven-year cycle, with, however, a lag of about one and a half years in the corresponding epochs. "It may," he writes, "be taken to be clearly established that the radius of the circle described by the pole of instantaneous rotation is greatest at times of sun-spot minima, and smallest at times of maximum displays of solar spots." This "holds true," he adds, "for the whole interval of about sixty years now covered by Dr. Chandler's investigations." His explanatory hypothesis is both simple and ingenious. It depends upon the large inclination of the earth's magnetic axis to its axis of figure, combined with alterations, due to solar influence, in the total magnetism of our planet. Molecular strains along the magnetic axis would—it is plausibly assumed—occasion bodily distortions of the globe, whence should result displacements of the axis of figure relative to the axis of rotation. "The outcome of this hypothesis would" then "be that changes in the state of solar activity, since they produce a measurable effect on the terrestrial magnetic forces, should also be accompanied by corresponding changes in the motion of the earth's axis."

The machinery by which electromagnetic impulses are propagated from the sun to the earth, completely evades scrutiny. Sundry conjectures on the subject have been hazarded, but none of them rest on any sure basis. What we know about modes of communication is chiefly negative. Thus, Hertzian vibrations are not transmitted to the earth with sunlight. They do not, at least, reach its surface. Wilsing and Scheiner tried for them in vain with an electric "bridge" and a galvanometer.[1] They might, indeed, as the experimenters noted, be atmospherically arrested. All that seems certain is that direct magnetic action is concerned in producing the observed perturbations of the terrestrial magnetic system, which are not explicable like ordinary meteorological

[1] *Wiedemann's Annalen*, Bd. lix. p. 782, 1896.

phenomena as effects of thermal vicissitudes, or convective air currents.[1] They stand apart, and imply special conditions which cannot, without detriment to science, be ignored.

Little progress has been made towards ascertaining the cause of solar periodicity. We are only assured that it is not imposed from without, but arises from within; it resembles a "free," rather than a "forced vibration." This conclusion, it is true, tends to relegate the matter to obscurity; for the interior of the sun is a *terra incognita*, and seems likely to remain so. His cyclical changes may belong to his original constitution; they may date from nebular times, and be as inherent as the tone of a bell. Or they may simply characterise a stage of growth, and prove liable to modification and effacement. The study of variable stars will perhaps help to guide our ideas as to the probabilities of the case.

Its full bearings, meanwhile, can only be conjectured. The scope of the disturbance needs to be defined. There are still many open questions connected with it. Does the "smoke-veil" absorption vary with the abundance of spots? Are the temperature of the photosphere, and the depth of the chromosphere affected by it? Can periodical changes of pressure in the reversing layer be detected? These are among the problems of the immediate future. They are already within reach of attack.

[1] Bigelow, *Report on Solar and Terrestrial Magnetism*, p. 15.

## CHAPTER XIV

### THE SUN AS A WHOLE.

MODERN science contemplates in the sun a huge sphere 867,000 miles in diameter, bounded by a dazzling cloud-shell, and composed of materials 1·4 times heavier than water, yet heated so far above the "critical temperature" of any terrestrial substance, that they must be regarded as in the gaseous state. The imperious demands of radiative emission can be met only by rapid exchanges, implying the unceasing activity of a system of profound vertical currents; while rotational surface-drifts of a peculiar kind notify complexities of internal movement defying speculation or research. Incidental to them, doubtless, are the dark spots marring, at times, the brightness of the disc, and giving evidence, by their more or less copious occurrence, of that far-reaching periodicity which may be called the central fact in solar physics. Spots are garlanded with faculæ, which represent photospheric upheavals; and above them, to a height of some hundreds of miles, rise the metallic vapours producing, by their absorption, the Fraunhofer lines. The reversing strata seem to be continuous with the chromosphere, although the nearly perfect transparency of the latter establishes a noteworthy distinction between the two formations; but the corona is a thing by itself, sharply separated, physically and spectroscopically, from every other appendage of the sun. It has, of course, relations with them, just as our air has with the ocean it surmounts—relations, however, that do not even verge towards a confusion of identity.

The two fundamental problems connected with the nature of the sun are its rotation and its periodicity. They may be

quite closely allied, and in regard to both, "counsels of despair" have begun to prevail. The spot-cycle, like "Carrington's law," is set down as a congenital peculiarity, and the mists of the past are invoked to cover the perplexities of the present. There seems little immediate prospect of their being removed. Early modes of investigating the subject have had no striking success, and fresh ones await development. So operations have come to a pause, yet by no means to a dead-lock. The difficulty of learning how the phenomena are occasioned should only stimulate diligence in unmasking and tabulating them. The ramifications of the period can be followed out, even if we cannot get at its roots, and there are signs that they will be found to take unlooked-for directions. Similarly as regards the sun's rotation. Explanatory hypotheses avail little, but the sifting of facts avails much. The case has not yet been fully stated. Lacunæ need to be filled up, anomalies to be smoothed away, errors to be corrected. In the doing of all this, a clue to the labyrinth may present itself.

The nature of sun-spots must long be under discussion. Questions of extreme interest are involved, some of them being visibly *answerable*, since criteria are at hand to determine which way the truth lies. Discriminative, rather than numerous observations will serve the purpose. The relations of faculæ with prominences offer another promising topic of inquiry, as well as those of prominences with coronal streamers. But this last is an eclipse-problem, and so, unluckily, is at present the entire subject of the corona. No pains, however, will be spared in order to bring to bear upon it the full resources of daylight investigation. As to whether they will be rewarded or no, the balance of forecast swings pretty even. The unfolding of some condition, now hidden, may incline it either way.

Solar spectroscopy presents a variety of aspects. It can be studied from the chemical, thermal, electrical point of view; pressure, density, motion, possibly magnetic stress, are concerned in it. Nothing in this branch, however, is more instructive than the spectral diversities of the various solar formations, or even of different parts of the same formation. Thus each section, some few miles thick, of the reversing layer is probably distinguished by emissive modifications; and

the Fraunhofer spectrum integrates the absorption of them all. The spot-spectrum is a more pronounced variety; the chromospheric spectrum is largely, the coronal spectrum, wholly peculiar. Now the task of interpreting these several scripts is not—could not be—easy; yet solar chemistry is, in the main, less unfamiliar than might have been expected. It includes only one element—coronium—that can be clearly distinguished as terrestrially unknown. For unidentified lines are not necessarily of exotic origin, as is proved by the rapid progress of their recognition in the Fraunhofer spectrum *pari passu* with advances in the photographic registry of metallic spectra. Nor is it probable that spot-cavities harbour strange forms of matter. The vaporisation in them of rare metals sufficiently explains what long appeared enigmatical in their absorptive action.

With the substitution of known for unknown substances in the sun, a leading argument for dissociation vanished. In this view, the supramundane species giving lines experimentally unrecorded were chemical fragments of our elements broken up by enormous heat. But if no supramundane species exist, the elements presumably remain intact. Absolute stability it would indeed be extremely rash to ascribe to them; yet it is certain that their individuality survives fierce ordeals. Evidence of other kinds tends towards the same conclusion. Mr. Jewell's critical examination of the Fraunhofer rays indicated for the shadings attached to certain iron and calcium lines an origin quite close to the photosphere.[1] This goes far towards demonstrating the integrity of extremely complex molecules at the highest temperature prevailing near the sun. Outbursts of heat from the interior there may be, reaching a still more exalted pitch; but they must be transitory, since cooling by expansion should promptly and potently affect them. Further, the thermal relations of the terrestrial elements are distinctive and uniform. If these bodies are not really simple, they are at least compounds of a different order from those known to be such, and artificially producible. Finally, the extensive detection of spectral series invalidates the "one line, one element" principle which underlies most of the arguments for dissociation. Unity of origin is emphatic-

[1] *Astroph. Journ.* vol. iii. p. 112.

ally claimed, not only by each series, but by each connected set of series. Researches into the essential nature of matter have, however, entered upon a new phase through the aid of what we may call electrical analysis, in which "ions" play the part of atoms in chemical analysis; and their outcome may perhaps aid in the solution of many intricate solar problems.

There is a strong temptation to transfer to the sun the conditions prevailing on the earth, and to model solar upon terrestrial meteorology. This was the line taken by M. Egon von Oppolzer in 1893. He admitted, indeed, that it traversed dangerous ground, in view of the wide divergences of opinion as to the nature of atmospheric processes belonging to immediate and everyday experience. Still he judged it safe to apply the kinetic theory of gases and the dynamical theory of heat to the determination of the state of equilibrium in the sun's aerial appendages. The results were scarcely encouraging. At elevations of one second of arc, or 450 miles, above the photosphere, the prevalent temperature was found to be 14,000° C. lower than at its surface, which should hence be extravagantly hot. And although this inconvenience was abated by forced assumptions, it could not, on the principles adopted, be removed. They involved, for example, a rise of temperature in downward currents to the extent of at least 5000° for each descent of 450 miles. Spots were regarded as "places of extreme alternations of temperature," [1] where abnormally hot layers cover anticyclonic regions of increased pressure and reduced thermal excitement. They are "produced indirectly through a sinking down of masses upon the photosphere, and directly through extraordinary radiation, brought about by transparency of the overlying region." To counterbalance descending movements in the spot-zones, a continuous uprising of heated matter was supposed to progress at the poles, constituted so far the analogues of our equatorial belt of calms. Two great permanent cyclones were thus centred on the axis of the sun. They had important functions assigned to them. Upon their regulative power was made to depend the working of the entire machine, and solar periodicity itself was referred to the alternate relaxation and enhancement of their activity. They were, nevertheless, a purely arbitrary creation. Not so

[1] *Astr. and Astrophysics*, vol. xii. p. 740.

much as a tortoise in mid-air was provided for the earth-bearing elephant to stand upon. The author claimed, it is true, only the merit of simplification; yet the contrast of conditions between the earth and the sun largely vitiated his reasonings. Atmospheric circulation on the earth is maintained by external heat; agitations on the sun by internal heat; they depend absolutely upon processes of cooling. Hence the impossibility of assimilation. Trade winds and cyclones lack in the sun the driving power by which they are kept going on the earth. They are characteristic of a planetary body—of a globe *vitalised* from without.

Eruptive hypotheses of the solar constitution have been proposed under various forms by a succession of writers—by Secchi, Faye, Lockyer, Schaeberle,[1] Young,[2] Sidgreaves.[3] Here, at any rate, we are in touch with reality. Volcanic forces are powerful in the sun, which might, in a sense, be described as organised upon a volcanic basis. The conditions of upheaval are everywhere at hand; only some casual relief of pressure, or access of heat is needed to provoke an actual explosion. Settling down on the photosphere in a cooled, though still gaseous state, the products of eruption would then give rise to spot-phenomena. Dark patches would mark the effects of their general and special absorption of light, while faculæ and flames attested the vehemence both of the original outbursts, and of those reactively started by their partial subsidence. Procedures of this kind on the sun appear inevitable; they at least count for something, if they do not explain everything.

A curiously subversive theory in solar physics was propounded in 1891 by Dr. August Schmidt.[4] Its interest, however, is largely academic. Yet it is no illusory speculation. It rests upon a sound foundation, and emphasises an undeniable truth. The mode of action brought into prominence by it necessarily plays a part in modifying the aspect of the heavenly bodies; the only question open is whether the part is conspicuous or insignificant.

The laws of atmospheric refraction were traced to their

[1] *Astr. and Astrophysics*, vol. xiii. p. 278. [2] *The Sun*, p. 187.
[3] *Astr. and Astrophysics*, vol. xii. p. 833.
[4] *Die Strahlenbrechung auf der Sonne*, Stuttgart, 1891.

ultimate consequences by Kummer in 1860.[1] Some of them are remarkable.

The visual lifting of extra-terrestrial objects results, as is familiarly known, from the inflected character of the paths pursued by light-rays through our air. A beam reaching a spectator at sea-level from a horizontal direction is really bent upward with a curvature one-seventh that of the earth itself. But on a globe of seven times the earth's radius—other things remaining the same—the refracted ray would possess identically the curvature of its surface, to which it would accordingly run parallel for ever, or until extinguished by absorption. It would never reach the eye of a spectator. "Circular refraction" would take effect upon it. A similar fate would befall a ray starting horizontally from the surface towards outer space, instead of attaining to which, it should follow an unending round within the air. On Jupiter, this critical stage must be considerably overpassed. From a Jovian atmosphere of the proportionate mass of the earth's, light could only escape at angles of elevation exceeding 3° 22′.[2]

Applying his formulæ to the sun, Schmidt found that circular refraction would there be produced in a hydrogen atmosphere at a temperature of 10,000° C., and of one-ninth the standard density of air. The upshot was to "explain away" most of the solar appendages. The photosphere he showed to be an optical illusion, arising at the surface where circular refraction just comes into operation in an incandescent gaseous globe diffusing uniformly outward. The difficulty was thus overcome of accounting for the visibly sharp separation between the dense body of the sun and its tenuous surroundings; while a phantasmagoria of granules, spots, flames, and faculæ was easily evoked on the supposition of irregular refractions within the seeming disc.[3] To this dubious locality, the reversing layer, too, was transferred by Dr. Knopf of Jena, who hailed the speculation as the dawn of a new era in solar physics. Hence, opposite displacements of the Fraunhofer lines cannot be a rotational effect, and the singular accordance of what they should be on that supposition with the measures actually obtained, is the outcome of pure

[1] *Monatsberichte*, Berlin, 1860, p. 405.

[2] Knopf, *Astr. Nach.* No. 3199.

[3] *Sirius*, 1893, p. 176.

accident. But this is extravagant and unthinkable—a *reductio ad absurdum* of the optically composed sun. Plainly, the whole theory is in the air. Its reasonings, to be sure, are mathematically valid; but they refer, as Dr. Seeliger has pointed out,[1] to an ideally transparent globe, from which the absorptive effects, prominent in the sun, are absent. The solar spectrum, besides, fails to be accounted for by them "on the accepted principles of physics."[2] Nor can practised observers of the solar surface readily be persuaded that they have watched, not realities, but mirage-effects. In dismissing the hypothesis as untenable, the important inference was, however, retained by Professor Frost "that refraction within and on the sun itself may modify in some considerable degree" observed phenomena.

An ingenious corollary has been added to Schmidt's theory by M. Julius of Amsterdam.[3] It was suggested by certain anomalies in the dispersive action of sodium-vapour upon light, noticed by Becquerel, and confirmed by himself. They led him far. He was conducted by them to optical explanations of the "flash" spectrum, of the broadening of lines in sun-spot spectra, and of line-displacements, usually interpreted on Doppler's principle. They are, however, given under reserve, and can be tested by comparing the lines affected in the sun with those in the vicinity of which special refraction is exerted. This is a laboratory task, which M. Julius himself is well qualified to discharge. Should the provisionally-assumed correspondences be found to subsist, the arguments for the phantasmic character of solar appurtenances will have gained imposing strength. But such a result cannot reasonably be anticipated. Refraction on the sun is likely, owing to the extreme rarity of the medium in which it should take place, to be of evanescent effect. Only in spot-cavities, it may perceptibly affect appearances. The entire matter, nevertheless, deserves to be thoroughly sifted, and cannot in future be forgotten or ignored.

Here again a fresh prospect is opening into view, and many others invite exploration by difficult and devious routes. For solar science does not become less arduous as it advances.

[1] *Astr. Nach.* No. 3187. [2] Frost, *Astroph. Journ.* vol. iv. p. 196.
[3] *Ibid.* vol. xii. p. 185.

One of the surest marks of progress in any branch is, indeed, the development of new and unforeseen problems. And the sun, as we have learned by degrees to recognise, is a body organised in too complex a method for easy apprehension. We perceive that its energies are specially directed; the purpose of the machine is obvious, and it is admirably fulfilled. In part we can see how, but much remains mysterious. Right to the core of the mystery we may never penetrate; nature is virtually invincible by man; but in urging our way forward, we shall gain continually larger and more lucid views.

# PART II.

## PROBLEMS IN SIDEREAL PHYSICS.

# CHAPTER I.

## PROGRESS OF SIDEREAL PHYSICS.

SIDEREAL physics includes stellar and nebular physics; the two branches cannot be separated. They have interlacing offshoots, and progress during the last hundred years has tended more and more to unite them in one main stem. Objects closely akin are dealt with in both, and they are dealt with by methods substantially the same. Stars and nebulæ are not only related as fellow-members of the grand galactic system, but they coexist in numerous sky regions, and often in such close connection that it is difficult to define them apart. A nebula with a stellar nucleus can scarcely be distinguished from a nebulous star, and nebulæ altogether devoid of star-like condensations are perhaps nonexistent. Chemical affinity ratifies visual conjunction. Spectroscopic classification proceeds from stars to nebulæ with hardly a break. The establishment of an exceedingly low standard of density for certain varieties of stars forges an additional link between the two sidereal orders. For it brings to our acquaintance bodies in a transition-stage from nebular diffuseness to solar condensation—bodies attracting feebly while radiating powerfully. Variability in light is another quality, the common possession of which by stars and nebulæ has recently been placed beyond doubt; and strong evidence is forthcoming that binary systems occasionally consist of a stellar and a nebular member, united by origin and inseparable to all time.

The methods of solar and sidereal physics do not differ fundamentally; all alike depend in the main upon light-analysis and chemical delineation, and resort to direct tele-

scopic observation only as a subsidiary expedient. The aims of sidereal science are, however, profoundly modified by the remoteness of the objects it is concerned with. Many kinds of inquiry, successfully prosecuted in regard to the sun, are impracticable for application to suns deprived by distance of sensible dimensions. Surface-phenomena are in them wholly out of reach, no less than the paraphernalia that lend their glory to total eclipses. No star sends us more than a single pencil of light, collected indiscriminately from a wide hemispherical area to the obliteration of its local peculiarities. Spots, flames, faculæ (if such there be) mix their rays inextricably together; for stars have no parts. But while their distance narrows in some directions the scope of possible inquiries concerning them, their multitude immensely widens it in others. They are not all similar, and their differences supply grounds for a classification, the import of which deepens with every advance in physical knowledge. Delicate spectral traits are found to be indexes to conditions of temperature, density, magnetic strain, or electrical excitation, in part imitable in the laboratory, in part transcending, and hence contributing to enlarge terrestrial experience. Classification, moreover, is dominated by the idea of development. Comparative sidereal study leads inevitably to far-reaching speculations on cosmical growth.

The sun is solitary; he exercises a "sole dominion." But it is not so with all his compeers. Nor are the mutual relations of those linked together expressed solely in terms of motion. They do not fall within the exclusive competence of the mathematical astronomer. They involve constitutional modifications of profound import. Coupled stars, clustered stars, stars immersed in or attached to nebulæ, are probably subject to influences, the nature and modes of action of which remain largely obscure. Their investigation has, however, been tentatively set on foot, and may give results of peculiar interest. Thus sidereal science extends and supplements solar science. It assigns to the sun its status in the universe; it provides objects with which it can be compared or contrasted. The two modes of knowledge mutually act and react; what one acquires the other assimilates. The progress of each is, by this comparative action, quickened and assured.

The population of the heavens is so dense that general conclusions as to its characteristics can be attained only by statistical methods. And to employ these effectively, the command of vast masses of information is required. Data must accordingly be secured wholesale, and the necessity has been met by the creation of a world-wide international organisation. But its mills grind slowly, and individual enterprise will not be stayed. Sir David Gill has already completed, in the *Cape Durchmusterung*, a preliminary work designed purely in the interests of geometrical astronomy, but fraught with importance to cosmical physics. Professor Kapteyn of Leiden, who undertook the examination and measurement of the plates, detected relationships between the kind of spectrum given by the stars imprinted upon them and the mode of their scattering, which promise to affect more and more profoundly all future conceptions of the universe. Hints of their prevalence had, it is true, been already gathered. Father Secchi noticed long ago that spectral types are not indifferently distributed over the sky, a conspicuous example of local preference being afforded by the constellation Orion, which might be described as a colossal group of helium stars. The work of Pickering, McClean, and others has also brought out the facts that the Milky Way is a distinctive spectroscopic region, and that the stellar tribes in general show aggregative tendencies not to be mistaken. Astrophysical considerations then enter into discussions of celestial structure; they are not wholly alien to questions as to how the heavens move. The monumental "Draper Catalogue" of stellar spectra served as the foundation of most of these extensive researches; and the entire bulk of photographic and spectrographic data collected at Harvard College with astonishing persistence and skill during the last score of years, has incalculably promoted the larger interests of sidereal astronomy.

Physical and descriptive catalogues of nebulæ are still a desideratum. The materials for their compilation are, indeed, lacking. Comparatively few such objects have been examined with the requisite care. They are not easily dealt with. Those of a gaseous nature are strongly characterised by rays high up in the ultra-violet, where absorption by glass is

formidably effective. Their due photographic registration is then feasible only by means of reflecting telescopes combined with prismatic apparatus of crystal and rock-salt, or some other materials transparent to the shortest wave-lengths. But since these special arrangements are rarely made, nebular spectrography makes slow progress. Its conditions, in the case of "white" nebulæ, are still more embarrassing. Nor are they much alleviated by substituting direct vision for the camera. All nebulæ are intrinsically faint, and most give continuous spectra. A scant supply of light makes, however, a much better show, as can readily be imagined, when concentrated in a few bright lines, than when dispersed uninterruptedly along the colour-scale. To the eye, the resulting variegated streak is dim and featureless; the sensitive plate takes cognisance of it only under the compulsion of prolonged exposures, and then imperfectly. The task of overcoming these obstacles is arduous, yet far from hopeless. It has been taken in hand, and on the success attending its prosecution the future of nebular physics essentially depends.

The discovery of helium as a terrestrial element marked a fresh point of departure in the chemistry of the heavenly bodies. Its leading chromospheric ray, $D_3$, had already been noted as an emission-line in the Orion nebula by Dr. Copeland, as an absorption-line in Rigel by Professor Keeler; but this was only preliminary to what was to follow when recognition-marks were multiplied by complete experimental acquaintance with the associates of the yellow beam. One of these, a line in the blue ($\lambda$ 4472), is much more conspicuous in stellar spectra than $D_3$, and it was established by Vogel in 1895, with other members of the conjoined series, as distinctive of a large class of "helium stars."[1] Some insight was thus gained into the extraordinary profusion with which this strange gas, so sparingly occluded by the earth, is dispensed to the suns in space. In order to show spectroscopically, it must, as already stated, be voluminously present in a glowing atmosphere. Its rays scarcely endure competition. Our sun, for example, although surrounded by huge volumes of helium, is not a "helium star." Pretty sure indications, on the other hand, can be gathered that helium

[1] *Monatsberichte*, Berlin, 24th October 1895.

is one of the principal components of all gaseous nebulæ; and it blazes where stellar incandescence is strong—in "new" stars, in bright-line stars, and in some "long-period" variables. The disclosure of its great cosmical rôle is among the most important consequences of the modern alliance between astronomy and terrestrial physics.

The identification of oxygen and nitrogen as stellar constituents by Mr. McClean and Sir William and Lady Huggins respectively, and the detection of the "Pickering series" of hydrogen in certain stars, are advances of scarcely less moment. These unusual kinds of absorption emerge, as a rule, in stars showing helium as well, and generally assumed to be at an early stage of growth. They apparently tend to supersede metallic action, which becomes imperceptible when the inchoate stage is approached. Thus the nebular spectrum includes no lines of known metals, and they are likewise apparently missing from "Wolf-Rayet" stars. Acquaintance with these remarkable objects has profoundly altered the views of stellar physicists. It has introduced them to a borderland where the prevalent conditions defy forecast. Who, for instance, could have anticipated Campbell's observations of mixed bright and dark spectral series, derived from the same element, in the same object? Nothing could well be more perplexing; but perplexities are often the raw material of discoveries.

The application of photography to the examination of "blaze stars" began with the apparition of Nova Aurigae in 1892. Opportunities for its continuance have since been frequently afforded, which would probably have slipped by unused but for the automatic watch kept on the changes of the heavens at Harvard College and its southern dependency. Two generalisations have thus been authorised. One is that the spectra of Novae are mainly composed of bright and dark lines in pairs, emanating from the same substances, but pushed asunder as if by the effect of swift opposite motions. The second is that fading Novae put on a nebular light-vesture. Spectroscopically, they simulate minute "planetaries." These surprising facts are seeds of future knowledge; they need time to germinate and yield fruit.

Stellar variability no longer remains outside the pale of

successful research. The mystery surrounding it has not, to be sure, been dissipated; but some of its attendant circumstances have become manifest. Eclipsing stars are now fully open to investigation; and although not physically variable, they have indisputable connections with stars that are. Fluctuations executed quite punctually in periods of a few days or hours indicate a compound nature in the objects undergoing them, even if they cannot be explained as occultation-phases. Short-period variables, in short, are non-eclipsing spectroscopic binaries. Yet spectroscopic binaries, indistinguishable from them as to their orbital conditions, shine with a perfectly steady lustre. And these are the majority. It remains to be discovered what are the special attributes of the differentiated classes. Nor is variability found only in conjoined objects. Stars apparently single are subject to extreme, although more or less irregular vicissitudes. The only clue to the nature of these vicissitudes yet found is the fact that increase of light is ordinarily attended by the spectroscopic flashing out of hydrogen-rays. Moreover, the resemblance of stellar light-curves to sun-spot tracings gives a strong hint that the solar analogy should be made a starting-point for inquiries into "long-period" variability.

The branch of stellar astronomy concerned with double and multiple systems gains extension and importance year by year. Their evolution under the influence of tidal friction has been studied by Dr. See. Sir William Huggins's device of a slit with reflective jaws having facilitated spectroscopic observations of close stars, the analysis of their light has at last entered upon a stadium of progress; apart from which perennial obscurity must have hung over sidereal chromatics, and enveloped theories of sidereal growth. Spectroscopic binaries, meanwhile, are multiplying on our hands, and their varieties offer a brilliant field for investigation. Their periods range from less than one day up to two years; some revolve in subordination to larger combinations; their orbits are variously inclined, and of various degrees of ellipticity; and one of the circulating bodies is, more often than not, sensibly devoid of light. The function and place in creation of "dark stars" have thus come into the foreground of inquiry. They occur also in telescopic systems, where their disturbing power

produces a visible *swaying* in the movements of their bright companions; but less commonly, it would seem, than as members of spectroscopic couples. These are, so to speak, just out of the shell; hence dark stars can hardly be effete suns, although suns presumably lapse with age into obscurity. The distinction is a delicate one to draw, but should not be lost sight of.

The scope of sidereal research is limitless — limitless because its objects are indefinitely numerous. The difficulty is to lay hold of them. Inferences based on partial surveys are felt to be unsatisfactory. The star-depths beyond continually invite farther and farther advances. Astronomical curiosity is only temporarily appeased by learning, for instance, the radial movements of a few score of stars; they are wanted by the hundred, and when at hand in hundreds, they will be in demand by the thousand. Exhaustive inquiries, while remaining unattainable, must, by the nature of the case, be perpetually aimed at. And what is primarily needed for them is a plentiful supply of light. Ambition in telescope-building is then justifiably insatiate, nor has it, so far, overreached itself. Each addition to instrumental capacity has, on the contrary, notably widened the horizon of feasible research. The erection of the great Lick refractor made it possible to obtain legible spectrographs of the Wolf-Rayet stars, and set the nebulæ in motion by enabling Professor Keeler to determine their radial velocities. With the Crossley reflector, mounted in the same superb situation, nebular photography made a fresh start, and the law of spirality, as a structural principle, was confirmed and generalised. The Yerkes telescope has given access to several closed fields. By its means, variable stars are followed through their semi-extinct phases. Professor Barnard has performed the unique task of verifying visually the rapid light-changes of the minute components of globular clusters; and Professor Hale has examined spectrographically a large number of "carbon" stars, too faint as well as too red for satisfactory treatment under average circumstances with the camera. The completion, at the same observatory, of a five-foot reflector will shortly afford even better opportunities for prosecuting this work. It may be added that a special function in nebular investigations is

reserved for instruments of abnormally short focal length, such as the Meudon reflector, in which the rays collected by a mirror thirty-nine inches across form an image at only thrice that distance from it.

Centuries, however, of invention and contrivance must elapse before the *minuta plebs* of the sky can be individualised by the peculiarities of their spectra. Inducements to keep up this strain of toil are not wanting. "A star's a star for a' that," even though it lie beyond reach of human questioning. To bring it virtually nearer, is the object of perpetual efforts. And they cannot fail to be rewarded. Novelties in the heavens are likely to prove endless and surprising. The enticements they offer to progress are irresistible. No "anchor dropt at eve or morn" can stay the ideal voyage. "When a man hath done, then shall he begin" his scrutiny into the works of the Most High.

## CHAPTER II.

### THE CLASSIFICATION OF STELLAR SPECTRA.

VARIOUS methods of classification may be applied to the stars. The most obvious and the most antique is that of relative brightness. From of old the stars have been collected into ranks by "magnitude." Or the amount of their "proper motions" may be taken as the principle of distinction. Within certain limits this is practicable, and for certain purposes it is useful. But apparent lustre and projected movement alike depend in part upon distance; they include an extraneous element; and astrophysical science considers the heavenly bodies in themselves, without regard to their spatial relations. Hence an absolute quality must be made the basis of their arrangement, and it is found in the *kind* of light emanating from them. This system is of far more than conventional value. It affords the only clue within reach to the intricacies of stellar constitution. Schemes of spectral classification may be amended and altered; but in one form or another they are indispensable to progress.

They naturally tend to become more complex as facts multiply, and finer shades of difference are rendered manifest; yet Father Secchi's four "types" continue fundamental. It is well, then, to keep their characteristics steadily in mind. The first is marked by strong hydrogen absorption. It consists of radiantly white stars. The second by innumerable fine metallic rulings; the sun is an example. The third type includes red stars with banded spectra like Antares, the bands being sharply terminated towards the violet, diffuse towards the red. The fourth is composed of deeply-tinted, mostly faint objects, showing wide bands facing redward,

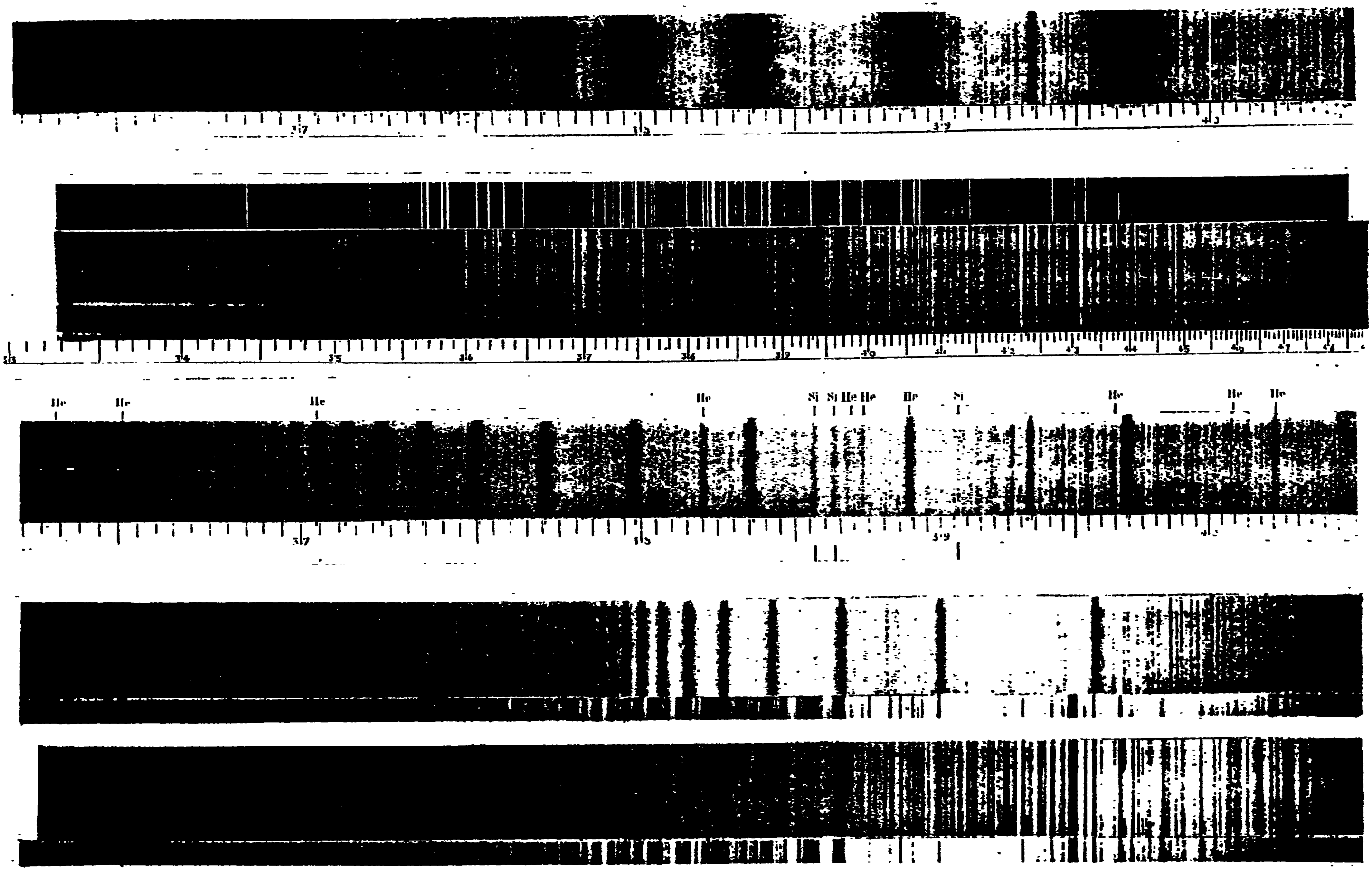
due to carbon absorption. These four groups form irremovable landmarks; but beside and between them many subordinate divisions have been set up. Vogel, Huggins, McClean have all modified, while broadly adopting Secchi's "law of order." They have, moreover, regarded it, not as a mere empirical formula, but as prescribed by the necessary conditions of development. Modes of classifying the stars have come to be equivalent to theories of their evolution. With this aspect of the matter, however, we are not just now concerned. The aim of the present chapter is to establish convenient distinctions without regard to their essential meanings. The unravelment of these will be attempted later on.

Miss Maury's arrangement of the stars[1] is designed for a life-history as well. It is the most elaborate yet put forward. Based on the examination of some 4800 spectrographs taken at Harvard College, it embraces 681 objects, disposed in a progressive series of twenty-two groups, most of which are further comprised within three collateral divisions, established to meet the visible necessity for a secondary characterisation. The work is a monument of industry and skill, and will long hold a place of standard authority; but the fine gradations it emphasises, although worth putting on record, are scarcely suitable for committing to memory. Our object here is to present large outlines, leaving minute shades of difference to be dealt with as occasion may arise. There is danger of stellar classification degenerating into a maze of provisional distinctions. The best remedy is to fix attention on the summit-ranges of the landscape; when they are clearly imprinted on the mind, mastery of detail can be safely and readily acquired.

A framework of eight compartments accommodates practically all the stars. The separation is easy and natural, and the "notes" of the various classes present themselves unmistakably. The constituents of the four first show absorption spectra only; those of the four last are marked by emission as well as by absorption. No hypothesis of growth or affinity is implied by the order of succession given to the bright-line objects; only the interests of clearness have been consulted

[1] *Harvard Annals*, vol. xxviii. part i. 1897.

PLATE IX.



Stellar Spectra photographed by Sir William and Lady Huggins.

Fig. I. Vega (α Lyræ). Fig. II. Arcturus (Fe and Ca for comparison). Fig. III. Rigel. Fig. IV. β Cygni, Blue Star : β Cygni, Yellow Star (solar comparison-spectrum).

in its choice. We will now briefly describe these stellar families.

Class i.—*Helium Stars.*—In the spectra of these brilliantly white stars, absorption by hydrogen and helium predominates. The complete "Huggins series" is stamped upon them, from the fundamental C to its "head" in the ultra-violet;[1] and at least twenty-six of the strongest helium lines, culled impartially from all the six series, show conspicuously besides. In a few helium stars, suspected of nebular relationships, the "Pickering series" of hydrogen is represented, while others betray the action of oxygen, nitrogen, and silicon. Metallic lines are faint and scarce; those identified belong to sodium, iron, calcium, and magnesium. Especially remarkable is the comparative prominence of the magnesium line λ 4481, to the exclusion of the triplet *b*, which takes the lead in the solar spectrum. The substitution, according to many authorities, indicates enormous heat. Scheiner's criterion for high temperature is precisely the development of λ 4481, and Professor Keeler remarked that the effacement of *b* marked a stage of heat beyond the possibility of artificial production.[2]

In these stars there is almost no general absorption; their photospheres are *unveiled.* Moreover, they seemingly possess reversing layers of very simple composition, to which circumstance their display of helium may, with much probability, be attributed. Originally included in Secchi's first type, they were separated from it by Vogel in 1895, on the identification of their distinctive lines with those of terrestrial helium; and their importance in the sidereal scheme was accentuated by McClean's spectrographic researches in the southern hemisphere. The lucid orbs of Orion and the swarming Pleiades are leading members of the class, which are also thickly disseminated in the Southern Cross, the Centaur, and the Greater Dog. Miss Maury's first six groups are subdivisions of helium stars, arranged in the assumed order of their development from a nebulous condition.

We are indebted to Sir William and Lady Huggins for permission to reproduce their admirable spectrograph of Rigel, the premier helium star (Plate IX. Fig. III.), and to Sir

[1] S. A. Mitchell, *Astroph. Journ.* vol. x. p. 32.

[2] *Astr. and Astrophysics*, vol. xiii. p. 661.

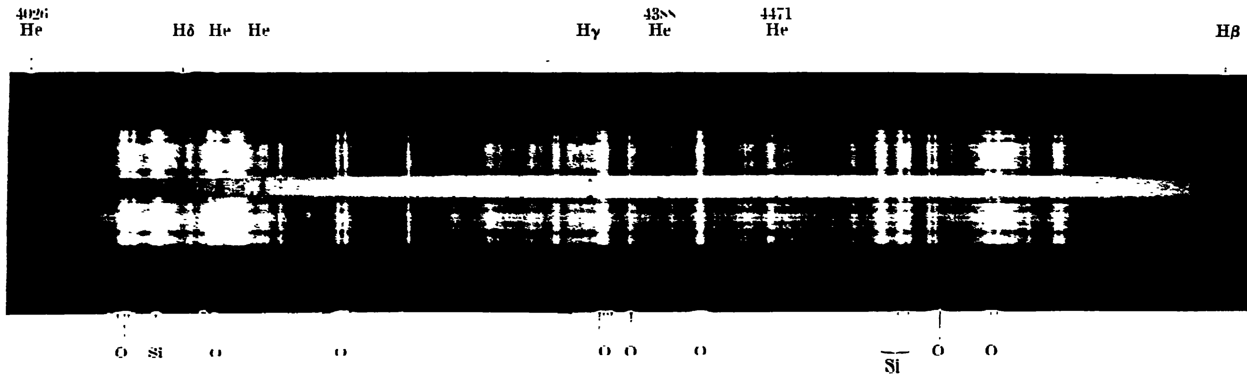
David Gill for that of $\epsilon$ Caius Majoris (Plate X. Fig. 1), taken by his assistant, Mr. Lunt, who detected many lines of silicon and oxygen, in addition to strong helium-absorption, in the spectrum of this star.

Class ii.—*Hydrogen Stars.*—These stars are distinguished by intense hydrogen-absorption of the ordinary kind, no Pickering lines being present. Helium-influence on their light is null, or barely perceptible. The "H" and "K" of calcium are thin but distinct. Feeble iron lines can be numerously discerned. General absorption is slight; the ultra-violet end of the spectrum lies open, imparting to hydrogen stars a bluish-white colour. Vega is a perfect example; its spectrum, photographed by Sir William and Lady Huggins, is shown in Plate IX. Fig. I. The black band to the right is the fifth line of hydrogen (H$\epsilon$). It masks the calcium "H"; but "K" appears well to the left.

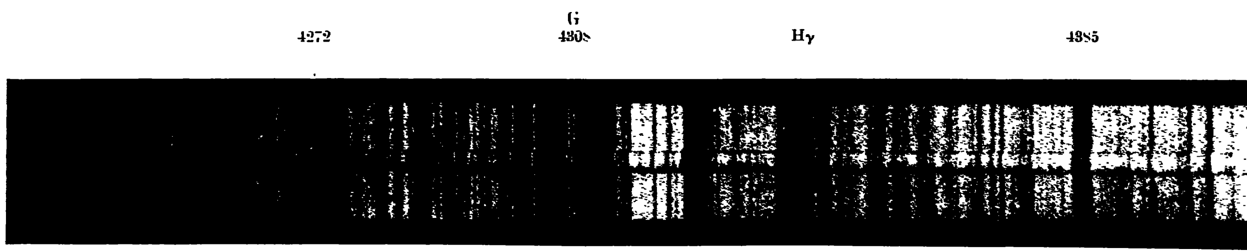
Hydrogen—sometimes called "Sirian" stars—abound in the heavens. They form the main part of Secchi's first type, and are distributed by Miss Maury into five groups, numbered vii. to xi.

Class iii.—*Solar Stars.*—The Fraunhofer spectrum sets a pattern copied, with slight variations, by the members of this class. Its leading feature is the powerful development of "H" and "K." Other metallic lines are innumerable, but mostly sharp and thin. Four hydrogen lines are normally present, ultra-violet members of the series showing decisively only in stars like Procyon and Canopus, which may be regarded as intermediate between the Sirian and the solar classes. A yellow tinge corresponds in the latter to a veiling of the blue end of the spectrum, similar to that perceptible in the sun. Solar stars, then, resemble him, not only in the composition of their reversing layers, but in the possession of "smoky" envelopes. A spectrograph of Arcturus by Sir William and Lady Huggins is shown in Plate IX. Fig. II., and one by Sir David Gill of $a_2$ Centauri, the brighter member of the southern binary, in Plate X. Fig. 2. The precision of its correspondence with the solar spectrum may be seen by a glance at the comparison strips in this latter figure. Stars of the solar class constitute Secchi's second type, and are included in Miss Maury's groups xii. to xvi.

1.




2.




1. Spectrum of ε Canis Majoris (central strip) compared with Lines of Hydrogen, Helium, Oxygen, and Silicon.

2. Spectrum of α Centauri (central strip) compared with Solar Spectrum (outer strips).

*N.B.*—The relative displacement is due to a difference of temperature at the exposure-times.

Class iv.—*Stars with Fluted Spectra.*—Two kinds of absorption are distinguishable in them. A linear system, somewhat reinforced from the Fraunhofer model, has superposed upon it a set of dusky flutings, about ten in number, of undetermined chemical origin. They suggest action by oxides, the formation of which in stellar atmospheres would seem to imply a considerable reduction of temperature. None of the bands occur in the more refrangible part of the spectrum, so that the photographic differences between solar and "fluted" stars are easily overlooked. Nor is there an abrupt transition from one class to the other. From Capella the line of connection passes unbroken through Arcturus and Aldebaran to $\beta$ Andromedæ and $\alpha$ Orionis (Betelgeux), absorption settling down more heavily on the blue rays, and metallic lines gaining strength at the expense of the truncated hydrogen series, until the fluted type is definitively formed. It is equivalent to Secchi's Type iii. Within its compass a progression of objects with deepening bands, such as Miss Maury has arranged in her Groups xvii., xviii., and xix., can readily be followed out. It may be said to terminate with $\alpha$ Herculis, a star of the third magnitude, displaying magnificent prismatic chiaroscuro. A drawing of its spectrum by Mr. Espin is copied in Plate XI. Fig. 1.

Fundamentally, the same series of bands recurs in all the individuals of this class. They vary from star to star both in relative and in absolute intensity, but their identity remains unmistakable. The presence of certain determinate atmospheric ingredients fixes the type, and no others can replace them. The stars belonging to it are in diverse degrees red or orange, their blue emissions being largely arrested in the precincts of their photospheres. They must hence be intrinsically brilliant far beyond the proportion of their visual, and, still more, of their photographic magnitudes. Their apparent lustre, that is to say, is small compared with the masses that may reasonably be assigned to them. Their light is markedly unstable, and many are subject to periodical variations of exceedingly wide range. These give bright-line spectra of a very definite character, which it seems advisable to set in a class apart.

Stars with fluted spectra (conveniently designated as

"Antarian,"[1] from their exemplar, the *lucida* of the Scorpion), although rare compared with Sirian and solar stars, are found plentifully in every part of the sky. No comprehensive catalogue of them exists; the number of those already known might, however, be roughly estimated at a couple of thousand. They must be vastly remote. None have sensible parallaxes, and very few show appreciable proper motions.

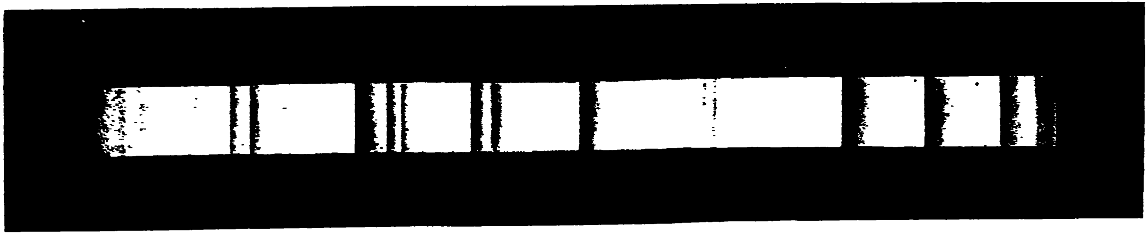
Class v.—*Carbon Stars.*—These have also banded spectra, but of a totally different stamp. Three shadings, particularly conspicuous in them, testify to strong absorption by carbon vapour. Vogel found them to reverse exactly the spectrum of an alcohol flame.[2] Scheiner conjecturally identifies the absorbent material with acetylene.[3] Others hold it to be pure carbon. There is much uncertainty on the point. The carbon-bands are of different degrees of obscurity in the various members of the class, nor do they in all preserve the same relative strength.[4] Subordinate bands, too, of unknown origin diversify these spectra more or less strikingly. But all are designed on the same pattern; it is only the mode of *printing off* that varies. They include as well many dark lines, notably Fraunhofer's "D" and "E," representing absorption by sodium and iron. A characteristic dusky streak at λ 576 awaits chemical interpretation.

Carbon stars glow like rubies in the sky; they are, for the most part, fiery red objects. To the eye they make a poor show. The brightest—19 Piscium—is of 5·5 magnitude; and only three in the northern and four in the southern hemisphere, out of about 250 recorded, exceed the sixth. This is not surprising when we consider that but a small percentage of their rays can escape stoppage by enfolding vapours. They would seem, besides, to be plunged in greater depths of space than Sirian or solar stars; so that they ought perhaps, allowance being made for these disadvantages, to take rank as potent light-givers. The coloured "zones," or luminous intervals in their spectra, are, at any rate, curiously vivid and sparkling. Most are to some extent, some are to a large

[1] This "short title" was first applied to them by Sir Norman Lockyer. See *Nature*, 18th May 1899. [2] *Potsdam Publicationen*, No. 14, p. 26, 1884.
[3] *Die Spectralanalyse der Gestirne*, p. 320.
[4] Dunér, *Astroph. Journ.* vol. ix. p. 131.

PLATE XI.

1.




2.

1. Spectrum of *α* Herculis. Drawn by Mr. Espin. 30th June 1894 (red end to the right).
2. Spectrum of 152 Schjellerup (yellow section). Photographed with the Yerkes 40-inch refractor.

extent, variable. Their photographic examination—rendered arduous by the quality of their light—afforded Professor Hale in 1898 the interesting discovery, imperfectly anticipated by Secchi, of several unfamiliar bright lines superposed upon their dark shadings.[1] Hydrogen lies low in carbon stars. It exerts no visible absorption, and displays no traceable emission. Their relationships with other stellar families are obscure; connecting spectral links are not altogether wanting, but they are of secondary importance. The class formed by them is coextensive with Secchi's Type iv. and with Miss Maury's Group xxi. Four specimens are given in Plate XII., from spectrographs taken by Professor Hale and Mr. Ellerman with a train of three prisms fitted to the eye-end of the Yerkes forty-inch refractor. The wealth of detail shown is so great as almost to obliterate the general columnar effect.

Class vi. — *Stars with Fluted Spectra showing Bright Hydrogen Lines.*—Mira is the typical star of this class. All its members (save one doubtful case) are pronounced variables. They fluctuate in colour too, but show in general a decided orange or ruddy hue. The flutings are very marked, and they tend to deepen and widen as the stars lose light. Essentially the same as in Class iv., they overlie a similar metallic line spectrum. Vivid hydrogen rays come into view with the approach of each maximum, and fade after it has passed. They seem, however, to persist much longer in some stars than in others. The series is, indeed, at all times incomplete. Its first term—the crimson C—is often missing; the second, F, is by no means invariably present; the stress of brilliancy is, in certain stars, laid upon the third, in most upon the fourth line, the fifth being always concealed by the dense, distended H of calcium. The succession of bright lines is resumed in the ultra-violet, and continued to the limit of the spectrum, which is curtailed by strong general absorption. A spectrographic impression of Mira by Father Sidgreaves is shown in Plate XIII. (1). It extends from orange to indigo, but stops short of H and K. There is no assured trace of green hydrogen, while the two blue beams are lustrous. A corresponding print of the spectrum of $\alpha$ Herculis appears on the same plate below that of Mira. The yellow ray

[1] *Astroph. Journ.* vol. x. p. 108.

of helium shines in some members of Class vi., and several dark lines in the spectrum of Mira coincide approximately with more refrangible lines of the same substance. Through the presence of emissive symptoms in fluted spectra, more than a hundred new variables have been photographically discovered by Mrs. Fleming and her staff at Harvard College. She subdivides them into eleven families, marked by the varying relative brightness of the hydrogen lines,[1] while Miss Maury includes them all in her twentieth group. Secchi's third type likewise claimed them; its limits were indeed defined before their singularities had been noticed.

Class vii.—*Helium Stars with Bright Lines.*—These objects give the characteristic dark-line "Orion" spectrum, variously emblazoned with rays of hydrogen, helium, and a few other substances. In some the bright and dark lines are ranged side by side, in others they are superposed, the system of reversal being tripled by the addition of dark *threads* drawn across the emission rays. The historical variable "P Cygni" exemplifies the former variety, $\gamma$ Cassiopeiæ the latter. The fundamental C is perhaps always the brightest line in these spectra, and there is a uniform decrease in the lustre of the hydrogen-series as it progresses upward.[2] In many cases its lower members show by emission, the rest by absorption. The bright spectrum may indeed be reduced to a solitary C. The same rule applies to helium. The circumstance, however, that the lowest terms of each series are those vivified, becomes evident only when the lines present are sorted out in their due sequential order. It is unapparent on a collective view of them.

About fifty bright-line helium stars are known, and fresh specimens are yearly swept up in the course of space-sounding operations at Harvard College. A fuller acquaintance was gained with thirty-two among the number by Professor Campbell's scrutiny of their spectra with the great Lick refractor in 1895. Much hesitation prevails as to their proper place in systems of stellar classification. Most usually they are treated as a subdivision of the dark-line helium class, but Miss Maury and Miss Cannon leave them outside the

[1] *Astroph. Journ.* vol. viii. p. 233.
[2] Campbell, *Astroph. Journ.* vol. ii. p. 181.

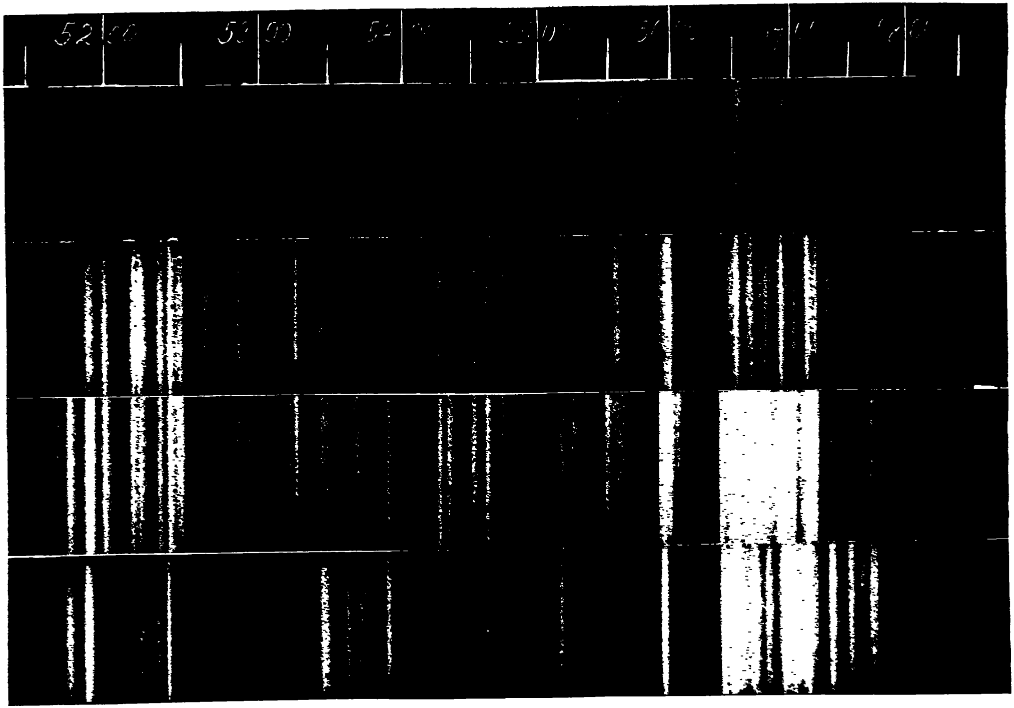
PLATE XII.

1.

2.

3.

4.



Spectra of Carbon Stars. Photographed with the 40-inch Yerkes Refractor by Professor Hale and Mr. Ellerman.

1. 280 Schjellerup (Mag. 7·8).
2. 19 Piscium (Mag. 5·5 Var.).
3. U Hydræ (Mag. 5·5 Var.).
4. 152 Schjellerup (Mag. 5·5).

framework of their respective schemes, appending valuable discussions of individual peculiarities.[1] There is much to be said for this mode of procedure. We are enabled, by the kindness of Father Sidgreaves, to reproduce in Plate XIV. a spectrograph of γ Cassiopeiæ taken at Stonyhurst, 7th March 1898. Among the bright lines imprinted on it are several due to magnesium,[2] namely, the *b*-triplet prominent in the sun, and the blue ray at λ 4481, specialised by Scheiner as marking a high grade of heat.

Class viii.—*Wolf-Rayet Stars.*—Acquaintance with these objects began in 1867 with the discovery, by MM. Wolf and Rayet of the Paris Observatory, of three small stars in Cygnus, giving a spectrum composed mainly of blue and yellow effluences. Then on 24th December 1871, Respighi [3] observed the brilliant prismatic radiance of γ Argûs (= γ Velorum), which proved to be of the same quality, although vastly superior in quantity. No other star of the kind exceeds the sixth magnitude, and over one hundred of them have been already recognised. Their distribution is remarkable; all are situated in or quite close to the Milky Way, except a considerable group located in the Magellanic Clouds;[4] and the Magellanic Clouds obviously reproduce many of the conditions of the Milky Way.

The leading spectroscopic distinction of the Wolf-Rayet class is the display of the Pickering series of hydrogen. Five of its constituent lines have been recognised, but they are not all equally bright. The upper ones may even appear dark. Emission-bands in the blue, on the other hand, never fail to be visible. Two at least are simultaneously or alternatively present. The more refrangible at λ 4688 is the azure beam identified by Rydberg with the leader-line of the otherwise unknown principal series of hydrogen. Its associate at λ 4652 may possibly owe its origin to nitrogen, but this remains to be proved. Helium lines show, both bright and dark, in these stars; in the same spectrum $D_3$ occasionally gleams golden beside its dusky fellow, the noted "Orion" absorption ray at λ 4472. Similarly, in the Huggins hydrogen

[1] *Harvard Annals*, vol. xxviii. pp. 49, 93, 100, 142.
[2] *Monthly Notices*, vol. lix. p. 507.
[3] *Comptes Rendus*, t. lxxiv. p. 516.
[4] Pickering, *Astroph. Journ.* vol. vi. p. 459.

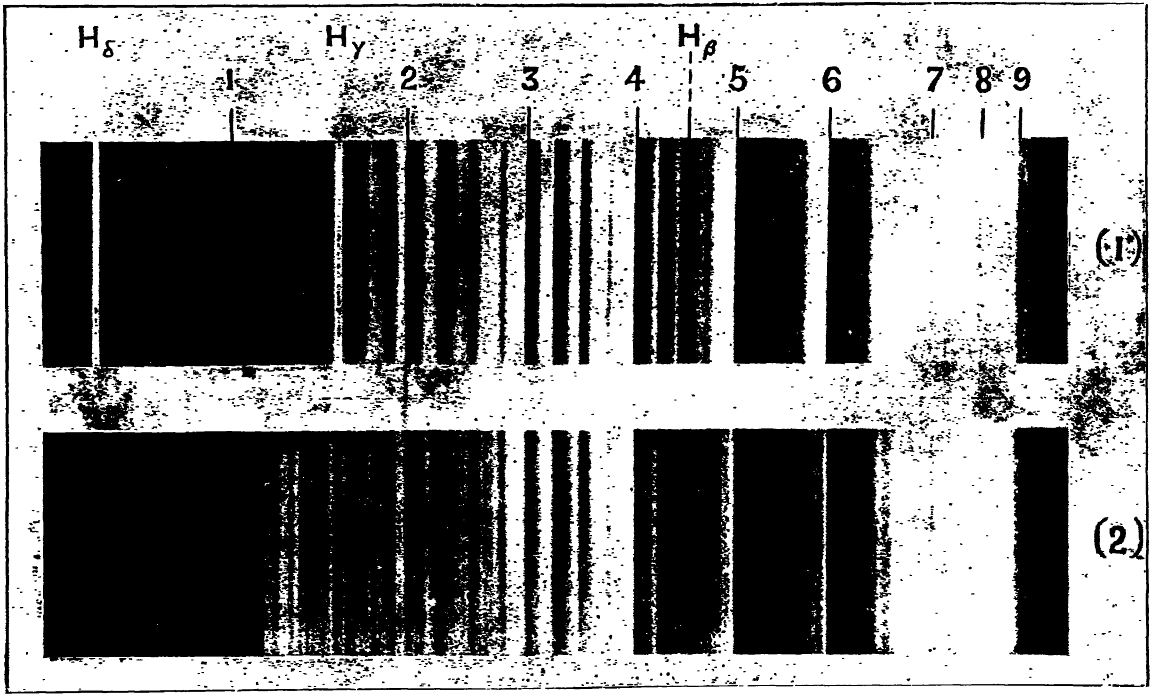
series, a vivid C may have for its companions an almost neutral F (H$\beta$), and obscure H$\gamma$ and H$\delta$.

The Wolf-Rayet spectrum is then triple. A band of continuous light, fairly strong in the ultra-violet, forms its basis. Absorption lines and bands are superposed, a few of them due to hydrogen and helium, but for the most part unclaimed by any terrestrial substance. To these are added hydrogen, helium, and anonymous bright rays in varying degrees of profusion. No metallic lines, bright or dark, have been recognised. Stars of this description are white or yellowish. They are rarely or never variable. Pickering combined them in 1891 with planetary nebulæ into a "Fifth Type of Spectra";[1] yet, certain nebular affinities notwithstanding,[2] they lie well away on the stellar side of the dividing line between the two sidereal realms.

The eight stellar divisions just enumerated comprehend as nearly as possible all the stars spectroscopically examined up to the present. The few left outstanding are, in general, difficult objects, which have been casually or defectively observed. When better known, they will probably avow affinities not at first sight apparent. Our classification may then fairly claim to be exhaustive; it certainly rests upon broad and unmistakable distinctions. And it is no small achievement to have obtained a bird's-eye view of the celestial "maze of error." Order is not knowledge; *vere scire est per causas scire;* but it is an indispensable preliminary to its attainment.

[1] *Astr. Nach.* No. 3025.

[2] Campbell, *Astr. and Astrophysics*, vol. xiii. p. 474.




Spectra of Mira (1), December 1897, and of α Herculis (2), February 1898. Photographed by Father Sidgreaves (*Knowledge*, vol. xxi, p. 113).

1 = λ 4227. 2 = λ 4420. 3 = λ 4581. 4 = λ 4757. 5 = λ 4951. 6 = λ 5162. 7 = λ 5447. 8 = λ 5597. 9 = λ 5756.

# CHAPTER III.

## HELIUM STARS.

HELIUM stars are often palpably connected with nebulæ. The entire Orion region, where they brilliantly congregate, is pervaded with cosmic fog; cosmic fog enwraps the Pleiades; and individual instances of the same association abound, and are likely to multiply as exploration proceeds. It is, however, visibly closer in some stars of the class than in others; and these nebulous gradations appear to correspond with spectral gradations of a very interesting kind, accurately represented in the progressive order of Miss Maury's groups. The earliest are strongly impressed, not only with helium and ordinary hydrogen lines, but with the Pickering series as well, noted by Mr. McClean to characterise a primitive stellar condition.[1] Satisfactory evidence of oxygen absorption in them was adduced by him in 1897, and lines of nitrogen and silicon are recognisable besides. Among metals only calcium and magnesium make a feeble effect,[2] the one with a just discernible K, the second with the "high-temperature" line in the indigo ($\lambda$ 4481). No sharp rays are found in these spectra. Their shadings take the form of hazy streaks.

The chief of a triple group in Monoceros is a specimen peculiarly worthy of consideration. It has the uncommon property, for a helium star, of being variable in a short period, whence its catalogue title of S Monocerotis; and it dominates a small cluster (N.G.C. 2264), measured by Bruno Peter in 1880.[3] An involving nebula, evasive of telescopic vision,

[1] *Phil. Trans.* vol. cxci. p. 129.

[2] Maury, *Harvard Annals*, vol. xxviii. p. 15.

[3] *Abhandl. der kön. Sächs. Gesellschaft*, Bd. xv. Th. 1.

came out fully in Professor Barnard's photographs of 1894,[1] and was described by him as "a very wonderful object, irregular in outline but quite well defined, with numerous black gaps running into it, and conforming in general with the peculiarities of the Milky Way in that region."[2] A picture on a larger scale was taken by Dr. Roberts a year later.[3] That S Monocerotis will prove to be a spectroscopic binary revolving in three days and ten hours, may be judged probable from the analogy of its fellows in variability.

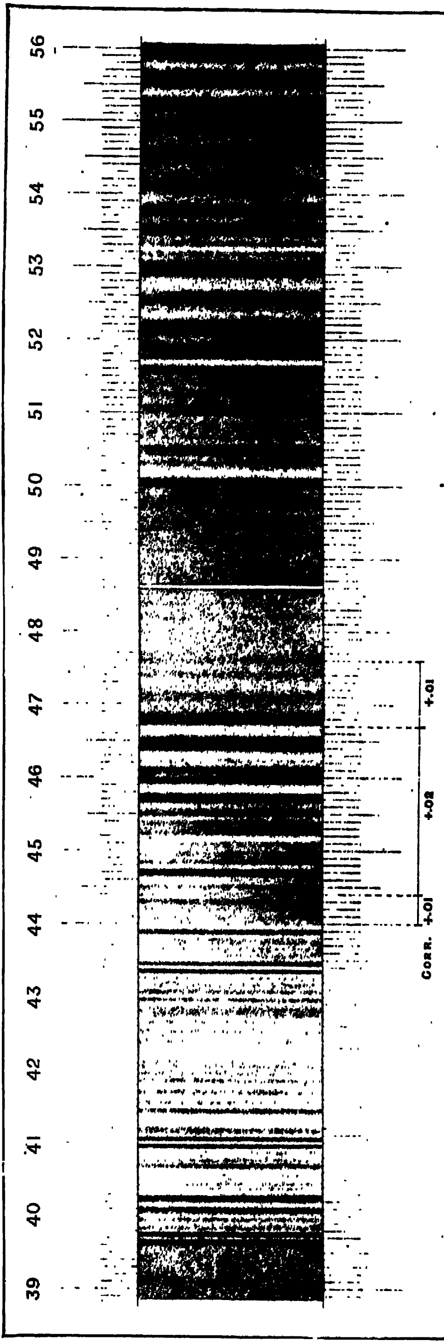
One of its contemporaries is the third magnitude star, ι Orionis (N.G.C. 1980). Sir John Herschel perceived it to be wrapt in a large feeble nebulosity, and a divergent streak, linking it to the great "trapezium" nebula, disclosed itself photographically to Professor W. H. Pickering.[4] It is widely triple, but sensibly stationary. Although its spectrum is in the main a copy of that of S Monocerotis, important distinctions may present themselves to scrutinising inquirers. Both the Wolf-Rayet blue bands show by absorption in these "early Orion" stars, the upper one being especially pronounced.

The three stars forming the Belt of the Giant are slightly more "advanced." Helium has gained strength in them relatively to the Pickering series; the reversal of Rydberg's azure band verges towards effacement, and in the middle star, ε Orionis, the spectral lines are fairly well defined. Oxygen, nitrogen, and silicon contribute each its quota of absorption. A great stream of nebulous matter sweeps through the Belt, and its two lower gems, ζ and ε Orionis, claim besides shining appurtenances of their own.[5] An analogous object, σ Scorpii, came out on Professor Barnard's photographs with a couple of nebulous "prongs" attached to it,[6] and also as a focus of marked condensation in the great nebulous field near Antares. The spectrum is perfectly similar to that of ε Orionis.

Among southern helium stars one deserves special mention if only for its association with a notable discovery. This is Mr. McClean's "oxygen star," β Crucis. His identification in 1897[7] of numerous lines in its spectrum as due to the

[1] One taken 1st February is shown in *Knowledge*, vol. xix. p. 109.
[2] *Astr. and Astrophysics*, vol. xiii. p. 178.
[3] *Knowledge*, vol. xix. p. 39.
[4] *Harvard Annals*, vol. xxxii. p. 66.
[5] ε Orionis=N.G.C. 1990.
[6] Barnard, *Pop. Astr.* Sept. 1897, p. 232.
[7] *Spectra of Southern Stars*, p. 11.

PLATE XIV.




Spectrum of γ Cassiopeiae, drawn from a photograph taken on March 7, 1898

Stonyhurst College Observatory.

absorptive action of our vital gas was fully confirmed two years later by Sir David Gill,[1] who employed for the purpose the splendid apparatus bestowed by Mr. McClean upon the Cape observatory. Silicon is also present, and the usual reversals of the indigo line of magnesium and of the violet K of calcium appear distinctly. Nitrogen, however, is not evident, nor the Pickering series of hydrogen. The spectra of $\beta$ and $\epsilon$ Canis Majoris, and of $\beta$ Centauri are of the same stamp. One of the brilliants of the Southern Cross, $\beta$ Crucis lies immersed in the Milky Way, at an unmeasured, perhaps an immeasurable distance from the earth. We have thus no means of estimating its actual radiance, which must, however, greatly exceed that of the sun. A secular proper motion of fourteen seconds is ascribed to it, and Sir David Gill finds it to be receding from the sun at the rate of about eleven miles a second.

Bellatrix, in the shoulder of Orion, is a typical helium star, the chief representative of Miss Maury's fourth group. No Pickering lines have been found in its spectrum, but Professor Keeler noticed the comparative prominence of a subordinate nebular ray at $\lambda$ 4390.[2] Nitrogen and oxygen were identified in it by Sir William and Lady Huggins,[3] and silicon by Sir Norman Lockyer[4] and Mr. Lunt.[5] The effacement of iron, remarkable in nearly all helium stars, subsists also in Bellatrix, and is explained by Sir Norman Lockyer as an effect of transcendental temperature. It has a spectroscopic *alter ego* in the *lucida* of the Southern Cross.

In the spectrum of Rigel some iron lines faintly emerge, and the sodium D appeared conspicuously on Professor Campbell's isochromatic plates. The Huggins series of hydrogen is magnificently displayed from its first term to the limit[6] (see Plate IX. Fig 3); helium lines are strong and numerous; those of nitrogen, oxygen, and silicon come out in photographs, and they were found by Sir William and Lady Huggins to be associated with certain distinctive rays of

[1] *Proc. Royal Society*, 27th April 1899.

[2] *Astr. and Astrophysics*, vol. xiii. p. 491.

[3] *Astr. Nach.* Nos. 3565, 3583. Bellatrix was one of McClean's original oxygen stars.

[4] *Nature*, vol. lxi. p. 263.

[5] *Astroph. Journ.* vol. xi. p. 262.

[6] *Ibid.* vol. x. p. 31 (Mitchell).

titanium.[1] The lines in this spectrum contrast markedly by their sharpness with those of other stars chemically similar, such as Regulus. Rigel belongs to Miss Maury's sixth group; it approximates to the stage where helium sinks out of sight, and yields the sole predominance to hydrogen.

In order to form some idea of its prodigious light-power we must remember that it has no sensible parallax (Gill), and is all but stationary in the heavens. This implies that it is so far off as to make almost no perspective response to the sun's centennial advance through space. In other words, a base line some thirty-three thousand millions of miles in length (allowing for foreshortening) shrinks to little more than a point as seen from Rigel. Assuming the reality of the minute proper motion of 1·5″ a century deduced from its catalogued places, and that it is a parallactic effect of our system's progress towards an "apex" on the borders of Hercules and Lyra, at the rate of twelve miles a second, we must ascribe to the star a distance of at least 367 light years, corresponding to an annual parallax of $\frac{1}{112}$ of a second. It follows that Rigel gives about 8000 times more light than the brighter component of *a* Centauri, an orb considered by Sir David Gill to be the exact match in every respect of our sun. But the sun is dimmed to about one-third of its native lustre by effects of absorption which are virtually absent from the star. Hence a total light emission 8000 times greater would represent a radiating surface only 2667 times more expansive than the solar photosphere. Rigel, moreover, is certainly not massive in the proportion of its luminosity. Stars of the helium variety are composed of highly rarefied materials. This has come to be known through the study of eclipsing stars. Taking, then, the density of Rigel to be about that of Algol, or one-fourth that of the sun, we find it even so to be of no less than 34,000 times the solar mass, while gravity at its surface is of just thirteen-fold power. Nevertheless its spectrum indicates extreme tenuity in its gaseous surroundings. Calcium, for instance, in the reversing layer of Rigel emits violet rays *only*. There is no trace of the blue line (λ 4227). The vapour exists there in much the same state as in the solar chromosphere and prominences—that is to

[1] *Atlas of Stellar Spectra*, p. 152.

say, in a state of the utmost attenuation, which implies the counterbalancing of gravity by a strong antagonistic influence, presumably of an electrical nature. This merely extends an inference already derived from solar phenomena.

The relationships of Deneb (*a* Cygni) have been variously assigned. There is, however, no longer any doubt of its affinity to Rigel.[1] The lines in its spectrum are numerous and clearly defined. Sir Norman Lockyer measured 307 on photographs of the section above F,[2] and there are hundreds besides. Those of helium are of subordinate importance; they are being replaced in the supposed evolutionary progression by metallic lines. Magnesium absorption is deeply graven in the ultramarine ($\lambda$ 4481), and begins to appear through the green triplet (*b*). Iron lines of the kind "enhanced" in the spark are fairly abundant; gallium shows at least one strong line,[3] and titanium lines are prominent. Among non-metallic substances, besides helium and hydrogen, only silicon is unquestionably present. It comes, however, well to the front. Mr. Lunt regards *a* Cygni, Rigel, and Sirius as some of "the best examples of silicon stars" yet known.[4] Nevertheless, spectrographs of them fail to show the three silicon lines most conspicuous in the $\beta$ Crucis group, while Lockyer's enhanced lines imprint themselves with some emphasis.[5] These celestial modifications of the silicon spectrum afford "valuable data," in Mr. Lunt's opinion, "for the elucidation of the problem of relative stellar temperatures." Their interpretation on current principles would lead to the conclusion that *a* Cygni, Rigel, and Sirius are hotter than the "earlier" suns typified by the "oxygen star" in the Cross. But there is no real certainty as to what causes the difference in kind between the luminosity of the spark and arc. Temperature may not be the sole, or even the chief, agent in its production.

The width and density of K in *a* Cygni are noted by Sir William and Lady Huggins as anomalous, calcium absorption usually remaining feeble when that of helium is visible. The

[1] Scheiner, *Sitzungsberichte*, Berlin, 13th February 1890.
[2] *Nature*, vol. lix. p. 342.
[3] Hartley, *Astroph. Journ.* vol. x. p. 164.
[4] *Astroph. Journ.* vol. ix. p. 267. [5] *Nature*, 16th March 1899.

curious thinness of the hydrogen lines may result in part from their projection upon a photospheric background of exceptional brilliancy.[1] The star, at any rate, is one of those which "stand apart through a distinctive individuality,"[2] and it invites, as such, special attention.

Regulus—an intermediate specimen—and $\beta$ Centauri are perhaps the only helium stars at determined distances from the earth. For the latter Sir David Gill found a parallax of 0·046″, equivalent to a light-journey of seventy-one years, so that it is by no means a near neighbour. In its place the sun would be just perceptible to the naked eye; it would appear of sixth magnitude, while the star is only a couple of grades below the first rank (its photometric magnitude is 1·2). Its emissions, in fact, surpass the solar radiance rather more than 150 times. We may then allow that they proceed from a photospheric expanse fifty times ampler than the sun's, which must encompass a globe 342 times more voluminous. Assuming further for $\beta$ Centauri (as for Rigel) a density one-fourth the solar, we obtain the result that it is of 85 times the solar mass. Owing, however, to the comparative remoteness of its surface from its centre, gravity has there less than twice the power which it exercises on the sun. Putting it otherwise, the acceleration of a falling body on $\beta$ Centauri is about 750 feet a second. The value of this "constant" is probably of essential importance in determining the character of stellar spectra; hence attempts at its estimation, despite the uncertainties that hamper them, are worth making.

The Pleiades are tolerably mature helium stars; Alcyone was selected by Miss Maury as the type of her fifth group. Some of its associates show hazy, others sharp lines. Algol approaches still closer to the boundary of the Sirian class, its "Orion lines" being quite secondary to the hydrogen set. Regulus is of nearly the same standing, but its spectral markings are dim and diffuse; those of inferior intensity thus make no appreciable impression, and the star's rays are all but exempt from absorptive encroachments.

They indeed tell but slightly throughout the entire class of helium stars, and this seems to indicate the absence of any

[1] Cf. A. Cotton on "Kirchhoff's law," *Astroph. Journ.* vol. ix. p. 244, note.
[2] Huggins, *Atlas of Spectra*, p. 148.

strong contrast in temperature between their photospheres and the encompassing incandescent vapours. That these are exceedingly tenuous is rendered almost certain (as already pointed out) by the non-reversal of the blue line of calcium. As to their relative temperatures, no dogmatic assertion is possible. The effects of transcendental heat evade inquiry. We cannot without hesitation assume that known rules apply under unknown conditions. The "temperature" of the electric spark is a purely conventional expression; to what state of matter it actually corresponds, can barely be surmised. Yet it is important to remember that the progression of helium stars—if the testimony of their silicon lines be credible—is *towards* this state from a lower degree of molecular excitement; while their "high-temperature" magnesium ray, present at the start, gains prominence by accordant gradations.

The inverse relationship between helium and metallic absorption is extremely significant. They seem to be almost incompatible; one tends to effacement with the incoming of the other. Yet it must be borne in mind that both subsist together in sun-spots, where a condition of things temporarily arises enabling helium to exert its proper stoppage upon light. Spot-spectra thus approximate, so far, to stellar spectra of the "Orion" stamp. Here, no doubt, we hold the clue to some profound physical analogy, the investigation of which may help to dissolve part of the mystery shrouding the "process of the suns." Moreover, oxygen, nitrogen, and "cosmic" hydrogen (if we may so call the modified gas giving the Pickering lines) are even more sensitive than helium to the adverse influence of metals. This statement is scarcely impugned by the fact that a trace of oxygen-absorption survives in the sun.

The closest connections of early helium stars are with members of the Wolf-Rayet family. But for the dusky lines of magnesium and calcium apparent in them, their spectra might indeed be said to reverse the Wolf-Rayet radiations. Later on, when nebular symptoms disappear, when helium fades, and faint iron lines crowd in, they slide imperceptibly into the Sirian stage of existence. No halt is cried. The frontier is crossed without advertence.

Helium stars are not equably scattered over the sphere. Their condensation towards the plane of the Milky Way, first noticed by Pickering,[1] was strongly emphasised by McClean's southern survey. "In the contiguous constellations of Musca, Crux, Centaurus, and Scorpio," he tells us,[2] "there are twenty-seven helium stars out of a total of thirty-six" brighter than 3·5 magnitude, and the proportion in Perseus, Taurus, and Orion is fifteen out of nineteen. It would be desirable to ascertain whether objects of inferior lustre are similarly swayed by this galactic attraction. But up to the present nothing is certainly known as to the prevalence of the type among faint stars. Below the sixth magnitude, its distinctive marks are hardly recognisable. The conjecture, however, is plausible that Milky Way aggregations are composed mainly of helium suns, large and small. But since their great intrinsic brilliancy renders them visible at distances completely quenching the rays of solar stars of the same size, they should preponderate in the Milky Way for this reason alone, apart from any real numerical superiority. So that the question of their distribution, like most others in stellar physics, has complex bearings. Helium stars are plunged, without any known exception, in abysmal depths of space. None have been found within a radius measured by about seventy years of light-travel. They frequent a sidereal region different from ours, where nebulæ linger and stars with blazing chromospheres have their habitat.

[1] *Astr. Nach.* No. 3025.
[2] *Spectra of Southern Stars*, p. 3.

# CHAPTER IV

## HYDROGEN STARS

HELIUM and hydrogen stars cannot be quite definitely set apart. The two classes commingle. A transition specimen of uncommon interest is found in $\eta$ Leonis, which combines some of the peculiarities of $\alpha$ Cygni with a powerful development of the hydrogen series.[1] Another is presented by $\theta$ Aquilæ, placed by Mr. McClean beside such clearly characterised helium stars as Algol and Pleione, but by Miss Maury in the group with Sirius and Vega. Even Vega, although a perfectly normal member of the hydrogen class, preserves a vestige of helium absorption in the typical "Orion line," $\lambda$ 4472; and its frequent companion, $\lambda$ 4026, emerges to view in stars like $\zeta$ Aquilæ, in which hydrogen approaches a maximum of strength. Both these lines are in the laboratory immediately associated with $D_3$, as members of the first subordinate series of the "yellow" helium set. None of the special Wolf-Rayet lines occur in hydrogen stars; the Pickering series is unrepresented; the "blue bands" have no dark counterparts; oxygen and nitrogen lines seem to have died out. Between the broad black bars of the Huggins series, however, crowds of ghost-like metallic rays are discernible. More than one hundred and thirty of these nascent markings were counted by Miss Maury in the photographed spectrum of Sirius, and her search, owing to the limited range of the plates, could only be partial.

Sirius is perhaps a slightly "older" star than Vega. Helium has entirely disappeared from its spectrum, and more familiar elements take its place—sodium, iron, magnesium,

[1] A. C. Maury, *Harvard Annals*, vol. xxviii. p. 24.

calcium, silicon, with titanium, vanadium, barium, and perhaps chromium and nickel.[1] A remarkable group of lines high up in the ultra-violet is of unsurmised origin. Photographed by Sir William and Lady Huggins 4th April 1890,[2] their approximate wave-lengths are λλ 3338, 3311, 3278, 3254, 3226, 3199, while the head of the hydrogen series stands at λ 3646. They are accordingly more refrangible than any possible hydrogen line; nor could impressions of them be obtained with apparatus including glass prisms or lenses, for which reason they are to be found only on the Tulse Hill spectrographs. The interpretation of these recondite characters offers an alluring problem. Although absent from the light of Vega, they will doubtless be recognised, when duly sought, in other Sirian stars; but exposures of the requisite kind are laborious, and seldom undertaken. Yet just such special investigations are likely to be the most fruitful.

Sirius is the best-known luminary of its class. This for two reasons. First, because of its vicinity. Light travels from the star to the earth in rather less than nine years. Next, because of our fairly complete acquaintance with the nature of its binary revolutions. They have now been closely observed during forty years, and their period is fifty-two. Hence the mass of the system has been determined, and it has, moreover, been apportioned with satisfactory exactness between the members. Their disparity in gravitative power proves to be small compared with their enormous inequality in lustre. The companion is a mere point of light outshone 36,000 times by its radiant primary, which is, nevertheless, more massive only in the proportion of 2·36 to 1·1. This quasi-obscurity of the Sirian satellite is very curious; but our present concern is with the majestic orb, in the blaze of which it is almost lost to view. From Dr. See's orbital elements, combined with Sir David Gill's parallax, a mass is deduced for it just two and a half times that of the sun. If, then, it were a body of the same average density and surface luminosity it should give nearly twice (1·84 times) as much light. In actual fact Sirius is of at least twenty-one times the solar brilliancy. This estimate is arrived at by taking $a_2$, the

[1] Frost-Scheiner, *Astronomical Spectroscopy*, p. 243.
[2] *Proc. Royal Society*, vol. xlviii. p. 216.

brighter component of $\alpha$ Centauri, as an intermediary. Sir David Gill has shown that its spectrum is a replica of the solar spectrum; its revolutions prove it to be of equal mass with the sun, and it is hence assumed with the highest probability to emit sensibly the same amount of light. It may accordingly, in comparisons of stellar brightness, be substituted for the sun, the uncertainty attending the direct confrontation of enormously unequal light-sources being thus avoided. Now the distances from the earth, and the photometric magnitudes both of $\alpha_2$ Centauri and of Sirius, are well known, so that it is easy to calculate how one star would appear in the place of the other. Sirius is twice as far off as the southern binary; transferred to that remoteness $\alpha_2$ Centauri would then show one-quarter its present brilliancy; it would be of 1·9 magnitude, just matching the chief star in the Plough. It would accordingly be 3·3 magnitudes fainter than Sirius, which is as much as to say that it gives only $\frac{1}{21}$ part of its light. And the sun, similarly located, would be of the same faintness.

Thus Sirius, while two and a half times more massive, is twenty-one times more luminous than the sun. Or, putting it otherwise, the solar ratio of light to englobed matter is exceeded more than eleven-fold. Three causes may concur to produce this effect. One of them we know to be present. It is quite certain that the Sirian beams are almost undimmed by self-absorption, whereas those of the sun are reduced probably to one-third their original intensity. A second contributory cause to the brilliancy of this star may be found in its great bulk. It is likely to be much less condensed than the sun, consequently to possess a much larger extent of photosphere relatively to mass. A luminous area multiplied four times would explain the outstanding disparity of brightness, but would involve a reduction of mean density to one-eighth the solar standard, or about one-sixth that of water. There remains the third factor of absolute areal brilliancy; but its value presumably depends upon temperature, and comparative stellar temperatures must for the present be left an open question. We are only able to conclude that *if* Sirius and the sun be on a par as to intrinsic shining power, then the star is probably about eight times more tenuous.

Vega is so much more remote than Sirius that it may safely be stated to quadruple its emissions. Its mass, however, remains undetermined, since it sways no detected companion with a measurable force. That it is small compared with its light can hardly be doubted. Indeed, throughout the hydrogen class, this rule prevails to all appearance universally.

The temperature of the stars, as already remarked, is one on which dogmatic assertions are best avoided. All authorities agree nevertheless that the conditions governing light-production in such orbs as Sirius and Vega approximate in many important respects to those present in a disruptive electric discharge. One important item of evidence to this effect is the prominence in spectra of this class of metallic lines weak in the arc, but strong in the spark. "The general result," Sir Norman Lockyer says,[1] "of the investigation of the enhanced iron lines in stellar spectra confirms the view that the absorbing regions of the hottest stars exist at a higher temperature than is attainable in laboratory experiments." Concurrent testimony was derived from variations of relative intensity in the magnesium and calcium lines shown by particular stars. But no allowance was made for modifications resulting from differences of pressure, which the Tulse Hill researches had proved to be highly influential. Hence the absence in Sirian stars of the "blue" line of calcium ($\lambda$ 4227) tells nothing by itself as to their temperature. The special value of Dr. Scheiner's magnesium-test is that the *opposite* behaviour of the two lines considered ($\lambda$ 4481 and $\lambda$ 4352) excludes the density-factor. For increase of heat may occasion the weakening of individual lines concurrently with the strengthening of others; but changes of pressure must always act in the same direction—though not necessarily to the same extent—on every element of the spectrum affected by them.[2] Professor Keeler[3] suggested that by means of the magnesium triplet, *b*, inferences as to temperature in stars might be extended to grades beyond the possibility of artificial production. This group is conspicuous alike in the flame, arc, and spark; it

[1] *The Sun's Place in Nature*, p. 305.
[2] *Sitzungsberichte*, Berlin, March 1894.
[3] *Astr. and Astrophysics*, vol. xiii. p. 660.

cannot be experimentally abolished, yet it fails (as we have seen) to appear in Rigel, and emerges very feebly in Sirius and Vega. Now it belongs to a subordinate series due to a special molecular arrangement, which could not easily persist in an extreme stage of heat. And a break-up of the arrangement would be marked by the effacement of the triplet in the green. "If this reasoning is correct," Professor Keeler wrote, "the aspect of the *b*-lines in stellar spectra gives us an extension of the method proposed by Scheiner, and it shows that the temperature of certain stars exceeds that of the most powerful electric spark."

The long range of powerful hydrogen lines in Sirian spectra, on the other hand, cannot be regarded as a sure symptom of excessive heat. It seems rather to indicate an approach to homogeneity in the originating stratum. The abridgment and enfeeblement of the series, and the development of metallic absorption, follow the same course, which is certainly not prescribed by thermal change. This inverse relation has not so far been satisfactorily accounted for. The most plausible hypothesis regarding it is that of Sir William and Lady Huggins, who connect it with the inevitable gain of effective gravity in condensing globes.

Nor can the intensity of the higher spectral sections be taken as an unequivocal sign that hydrogen stars are hotter than the sun. For it may be caused not by the intrinsic emissive superiority of their photospheres, but by their unveiled condition. We know that the sun's more refrangible rays would, through the removal of his absorbing atmosphere, acquire strength enough to turn the balance of colour from yellowish to bluish, and it is amply possible that its spectrum, displayed to equal advantage with that of Vega, might rival or outdo its actinic compass.

Fomalhaut ($\alpha$ Piscis Austrini) is a fine example of an advanced hydrogen star. Metallic lines are considerably more developed in it than in Vega or Sirius; the McClean spectrograms show a profoundly grooved K-line, and its blue associate ($\lambda$ 4227) is faintly reversed. The "spark ray" of magnesium ($\lambda$ 4481) is prominent. Miss Maury prints a table of wave-lengths[1] measured from the Harvard spectro-

[1] *Harvard Annals*, vol. xxviii. p. 27.

grams of this star which deserves particular attention as a record, perhaps, of a transition epoch in stellar growth. Lines of iron, titanium, and silicon are readily identifiable in it, but most of the entries have no obvious meaning. Fomalhaut is of 1·3 magnitude, and Sir David Gill has determined for it a parallax of 0·13″ showing it to be almost six times more remote than *α* Centauri. Its real brightness is hence easily found to be fourteen and a half times that of the sun. Its mass and density, however, remain entirely unknown.

As illustrating the physical differentiation of bodies to all appearance chemically similar, two stars may be singled out. These are Castor and *γ* Ursæ Majoris, the third of the Plough. Both are included in Miss Maury's Group viii., and both show deep and broad furrows of hydrogen. The spectra, in fact, bear the same inscription, only printed from dissimilar types. In *γ* Ursæ, the spectrum of Castor is viewed, as it were, out of focus. The lines distinct in the one are hazy and diffuse in the other; none probably are really missing, though a good many are effaced by expansion. This peculiarity is met with in a considerable number of helium and hydrogen stars forming Miss Maury's "division *b*." In "division *c*," on the contrary, of which *α* Cygni is the best exemplar, the lines are notably sharp and narrow, while in "division *a*" they are of normal appearance, some thin, others fringed or winged. The cause of these variations is obscure. It would naturally be connected with differences of pressure in the stellar reversing layers; and this again must depend in great measure upon the locus of absorption, which probably varies, not only from star to star, but for each separate substance in the same star. So that the conditions to be regarded, even from this point of view alone, are highly complex.

# CHAPTER V.

## SOLAR STARS.

THE transition from hydrogen to solar stars is effected as gradually as the transition from helium to hydrogen stars. Metallic absorption comes more and more to the front in successive objects, while the Huggins series retires into the background. There are no definite stopping-places; the course of change flows on continuously. At a certain stage of progress, however, the characters distinctive respectively of the condition that has been, and of the condition that is about to be, appear evenly balanced. The hydrogen lines, although reduced to about one-quarter their Sirian intensity,[1] still muster strong even in the ultra-violet, the metallic spectrum being at the same time pronounced and crowded. This medium state can be studied to advantage in Procyon, the lesser Dog star. So perfect is the blend of types shown by it, that Professor Pickering found it difficult to decide whether the spectrum was actually intermediate, or combined the Sirian and the solar light of two separate, but closely conjoined stars.[2] Either alternative is possible, but the former is the more probable. Nevertheless, the presence of the full complement of Huggins lines, together with a K-band of ten-fold the intensity possessed by it in Castor, must be regarded as somewhat anomalous.

Procyon is one of our nearer neighbours in space. Dr. Elkin has measured for it a parallactic shift of 0·325″, corresponding to a light-journey of ten years. And the revolutions of a faint companion complete the data requisite for

[1] A. C. Maury, *Harvard Annals*, vol. xxviii. p. 30.

[2] *Astr. and Astrophysics*, vol. xii. p. 720.

finding the mass of the system. It comes out 2·7 times that of the sun, and we cannot be far wrong in assigning to the brilliant component twice the solar quantum of matter. It gives nearly quadruple the solar light; yet the disparity between light and mass is notably reduced from the Sirian standard. Absorption has increased as condensation has progressed. The rays of Procyon are perceptibly tinted with yellow.

A similar spectrum is shown by the splendid Canopus. The extreme remoteness of this orb, which is second only to Sirius in apparent lustre, compels us to attribute to it a prodigious real light-power. It has no measurable parallax, and no sensible proper motion. Only a minimum estimate then of its magnitude is practicable. Sir David Gill attached to the zero representing its parallax a "probable error" of 0·011″. Hence the measures executed do not exclude a parallax of this amount, although they are just as consistent with an equal negative value. Canopus then may be no further off, but cannot be nearer than a light-journey of 296 years. Admitting, for the sake of illustration, that it is in fact at this distance, which is thirty times that of Procyon, we obtain the astonishing result that it gives no less than 3600 times its radiance. And since the spectra of the two stars agree nearly line for line, this figure must represent approximately the ratio of their photospheric areas, that of their cubical contents being 216,000 to one. In other words, 216,000 bodies of Procyon's size would go to make up one such globe as the star of prehistoric Egypt. Yet Procyon, as we have seen, is a sun constructed on a larger scale than our own. The existence of a luminary so vast as Canopus, although bewildering to imagination, need not appear incredible when we consider the immense scope of creation, and the boundless resources variously displayed throughout the ethereal spaces populous with stars.

Another interesting specimen of the Procyon variety is $\gamma$ Cygni. Visually of 2·3, it is only of 3·2 photographic magnitude. This implies blue absorption to an extent unusual in the presence of the ultra-violet hydrogen series. It is accompanied by a disproportionately strong K, well brought out in Mr. McClean's spectrograms.[1] The star resembles

[1] *Phil. Trans.* vol. cxci. plate 6.

$\alpha$ Cygni in the definite character of its lines, although their chemical meanings are very different. They have, however, as yet been most imperfectly deciphered.[1] The spectroscopic relations of $\gamma$ Cygni derive added importance from its apparent connection with a far-spreading galactic nebulosity photographed by Wolf and Barnard. But the star may be merely seen in projection upon it. The peculiarities of its light recur with less accentuation in that of Polaris.

A very close approach is made to the solar spectrum by $\chi$ Orionis; virtual identity is reached by Capella, $\eta$ Boötis, and $\alpha_2$ Centauri. It is scarcely compromised in Arcturus, or any of its numerous associates in Group xv.; the same lines subsist, only drawn somewhat more heavily, and there is an added shade of ultra-violet absorption. The steadiness with which the solar type is maintained, all but unmodified throughout a large collection of objects, is very remarkable. Of the 681 bright stars investigated by Miss Maury, 19 are Capellans, 111 Arcturians; the latter are barely distinguishable one from the other, the former only by the finest grades of difference.[2] This seems to indicate a particularly stable phase of stellar existence. Our sun's constitution, we can infer, is adjusted to a high degree of permanence; he is moving along a nearly level tract of his evolutionary journey, and will decline with extreme slowness from his actual state.

Solar stars are to be found of all sizes, their variety in this respect forming an instructive commentary upon their spectral similarity. Consider Arcturus. Dr. Elkin, from a long series of skilfully planned observations, assigned to it in 1897 a parallax so small (0·024″) that its light cannot reach us in less than 136 years. And since at this abysmal remoteness it outshines the sun's twin, $\alpha_2$ Centauri, by one-third of a magnitude, the actual excess of its brightness must be at the very least thirteen hundred-fold. In view, then, of its spectral identity, Arcturus may confidently be asserted to possess a photosphere 1300 times more extensive than the sun's. The globe it encompasses is, accordingly, about 47,500 times more voluminous, and in the same proportion (assuming equal mean densities) more massive. It

[1] Fowler, *Knowledge*, vol. xx. p. 78.

[2] *Harvard Annals*, vol. xxviii. p. 39.

follows that gravity exercises over the surroundings of Arcturus thirty-six times its solar power. Yet its spectrum bears no trace of sensibly augmented pressure. We are confronted everywhere in sidereal physics with this seeming inconsistency between the nominal force of gravity and its effective action.

Pollux ($\beta$ Geminorum) conforms strictly to the spectral pattern of Arcturus. It is, however, a full magnitude fainter and at only half its distance; it must accordingly be a much smaller body. Its superficial area is, in fact, one-tenth that of Arcturus. Nevertheless it contains fifteen times more matter than the sun, and gravity at the surface of Pollux has more than eleven-fold its solar power. Planets revolving round this star would have, at the same distances, periods about one-quarter the length of those belonging to the earth and its sister worlds, our year, for instance, being reduced to ninety days, so that a whole summer would be consumed in a brief holiday excursion.

But there are small as well as large solar stars. An insignificant object in the Great Bear, catalogued as "Groombridge 1618," and noted for its rapid proper motion, is, according to Sir Robert Ball's measures, comparatively near the earth, its light reaching us in 10·2 years. The sun, however, in that position would be four and a half magnitudes brighter, for it radiates fifty times more powerfully. The spectrum of 1618 Groombridge is of the Arcturian sub-class, so that the proportion of its mass may, under reserve, be taken to follow the proportion of its light. About 350 such stars, then, should be put into the scale to balance one sun, and gravity at its surface has one-seventh its value at the photospheric level. Another minor sun is "Bradley 3077" in Cassiopeia, although the inferiority is here slighter, since Bradley's star emits perhaps ten times more copiously than Groombridge's. Further examples of the kind will certainly come to be known when some progress has been made with the investigation of faint spectra. But this is most baffling work, subject to the illusions that everywhere haunt the limits of distinct visibility.

Enough has been said to make it clear that the Fraunhofer spectrum is exactly copied in orbs of most various

dimensions. This points, in Dr. Scheiner's opinion,[1] to the closest agreement, not only in the percentage of the chemical elements entering into their composition, but also in conditions of temperature and pressure. How such uniformity can be combined with widely different gravitational constants, is extremely hard to understand. The Tulse Hill experiments, already referred to, showed the predominant influence of pressure in altering spectral characters. Since, then, they are the same in Arcturus and Groombridge 1618, there is practical certainty that the calcium envelopes (for instance) of both stars do not differ appreciably in tenuity. Yet the compulsive force acting upon one is 252 times more powerful than that exerted on the other. The persuasion that it is somehow neutralised is irresistible. We might even venture tentatively to define solar stars as bodies in which the ratio is the same between gravity and electrical repulsion. In the course of time, doubtless, it will change; one or the other force will gain relatively to the other, and the spectral type will vary to correspond. Presumably the augmentation of strength will be on the attractive side; but cosmical electricity is still an unexplored region.

The symptoms of approach towards the fluted description of spectrum set in gradually, and are of two kinds. General absorption of the more refrangible rays spreads and deepens, and specific absorption becomes intensified in certain dusky lines. Conspicuous among these is the "blue" line of calcium ($\lambda$ 4227), the stress laid upon which unquestionably signifies increased density in the absorbing vapour. This is just what might be expected to accompany the progress of cooling and contraction, through which *domestic* gravity gains advantage, as acting in a steadily narrowing sphere. The symptoms described are visible in $\alpha$ Hydræ and $\beta$ Cancri; they are particularly well marked in Aldebaran. The last is a glaringly red star, its blue emissions being mostly arrested by its own atmosphere. Incipient flutings, too, are traceable. It is the "type star" of Miss Maury's sixteenth group, which includes twenty-three objects scarcely to be discriminated as regards the quality of their light. "From the greatly-increased width

[1] *Astronomical Spectroscopy* (Frost), p. 266.

in them," she writes[1] of the line at λ 4227, "it would appear to be complex, and to include lines weak or absent in the stars of the solar type."

Aldebaran has a parallax of one-tenth of a second, and is of standard first magnitude. Its real brightness is then certainly twenty-eight times greater than that of the sun; and since it has suffered much more heavily from absorptive encroachments, the emitting surface must proportionately exceed the spread of the photosphere. Even apart from any allowance for increased density, the Taurus luminary may be considered by a quite moderate estimate to be of 200 times the solar mass. On the other hand, the primary member of the famous pair, 61 Cygni, which as to spectrum is a faint duplicate of Aldebaran, ranks very low in the hierarchy of suns, emitting, in fact, only $\frac{1}{364}$ the light of that great red orb. Here, again, the lesson is enforced that the widest variety of size and mass may consist with spectral identity. Aldebaran is encompassed by gaseous strata apparently no denser and no hotter than the absorbing layers in 61 Cygni. This circumstance is evidently of vital moment in stellar natural history.

[1] *Harvard Annals*, vol. xxviii. p. 40.

# CHAPTER VI.

## STARS WITH FLUTED SPECTRA.

THE blue light of these stars is powerfully absorbed by an intensification of the screening effect observed in the sun. They are accordingly rufous, or red. Their spectra are profoundly scored besides with metallic rays, generally agreeing in position with, although differing in relative intensity from, the Fraunhofer lines. Thus the calcium line in the blue has gained still further upon the great pair in the violet than in transition stars of the solar type. Finally, banded absorption has come in. A complete system of ten or eleven flutings, sharp towards the violet, graduated insensibly towards the red, shadows nearly the entire visible spectrum. It is printed in stereotype. The bands are variously impressed, but similarly located, in all members of the class. This gives strong assurance of an identical origin. We do not yet know how they are produced, or by what substances, but there can be no doubt that their explanation in one star will apply to all.

With high dispersion the bands can be resolved into fine lines set very close together.[1] The fluted effect is due to the crowding of these lines towards a limiting wave-length prescribed, beyond question, by a rhythmical law. For that each band represents, as it were, a condensed series there need be no hesitation in admitting. Indeed, by mere reduction in scale the hydrogen procession in a white star assumes the aspect of a genuine fluting. A promising start has even been made in the research of laws regulating the distribution of lines in bands.[2] Each of the stellar stripes is then, so far, a

[1] Dunér, *Sur les Étoiles à Spectres de la Troisième Classe*, p. 9.

[2] Thiele, *Astroph. Journ.* vol. viii. p. 1.

separate entity, while all may be linked into harmony by subordination to some higher unknown principle. Whether they originate from one or many forms of matter has still to be determined; nor is there any certainty as to whether elements or compounds are concerned in their production.

Stars of Secchi's third type, forming the class just now under consideration, are divided by Miss Maury into three groups. Antares and $\beta$ Andromedæ belong to the first of these ("Group xvii."). They show all the characteristic bands, slightly marked, and transparent enough to allow every detail of the linear spectrum to be clearly visible. Betelgeux ($\alpha$ Orionis) is the pattern of the next group. Its prismatic light makes a beautiful and wonderful effect. The usual multiple absorption is exerted upon it, but with a delicately balanced power. The blue rays retain appreciable vivacity; the flutings are not so deep as to obscure the underlying rays; they are finely shaded, yet exquisitely distinct. Ten were measured by Vogel and Dunér, the strongest of which are the fifth and seventh, with their *steep* sides at $\lambda$ 5453 and $\lambda$ 5169 respectively. Battalions of dark lines show through them. On the Harvard plates Miss Maury counted 463, mostly composite, between the sodium D and the calcium H. The latter and its associate, K, have shrunken somewhat from their giant dimensions in Arcturus.[1] Iron absorption predominates. The rays significant of it are more prominent than in the sun, and some have unilateral shadings—a feature also visible in the spectra of sun-spots and of metallic oxides, and indicative probably of a decline in heat.[2] Professor Keeler remarked that the lines in Antarian stars "are essentially those of the solar spectrum, but the relative intensities are not the same, and the general aspect of the spectrum is quite different from that of the spectrum of the sun. The strong lines are mostly those of iron—apparently the low temperature lines. Their relatively greater strength in the star spectrum gives to some well-known solar groups (notably the *b* group) quite an unfamiliar aspect."[3]

Hydrogen-absorption is much more effective in Betelgeux

[1] *Harvard Annals*, vol. xxviii. p. 42.
[2] Frost-Scheiner, *Astr. Spectroscopy*, p. 308.
[3] *Astroph. Journ.* vol. vi. p. 423.

than in any other spectrum of the fluted kind. It is, however, distinctly, though feebly represented in all by the four lowest members of the Huggins series. The rest are either absent or shrouded in overlying vapours.

In $\rho$ Persei, a star capriciously variable between 3·4 and 4·2 magnitudes, the bands are perceptibly deeper than in $\alpha$ Orionis. On the other hand, the metallic rays seem rather less numerous and intense. But this diminution may be more apparent than real. The comparative faintness of the light they interrupt would partly account for it, and the added density of the associated flutings would help towards effacement.

Their still greater opacity in $\alpha$ Herculis occasions effects of contrast with the vividly tinted bright zones, described as "singular and magnificent," by Father Secchi, one of their earliest observers (see Plate XI. Fig. 1). Professor Keeler, whose study of fluted spectra was based on photographs of high dispersion showing manifold details, found the dark groovings, plentiful in $\alpha$ Orionis, to be present only as a comparatively scanty survival in $\alpha$ Herculis. Miss Maury reached a similar conclusion. Yet Dr. Vogel was struck with the richness in absorption-lines of this spectrum and the analogous one of $\beta$ Pegasi.[1] Both these stars vary irregularly, $\alpha$ Herculis from 3·1 to 3·9, $\beta$ Pegasi from 2·2 to 2·7 magnitude. Next to Antares, the brightest specimens of this class in the southern hemisphere are $\gamma$ Crucis and $\beta$ Gruis. Mr. McClean obtained spectrographs of all three at the Cape in 1897.[2]

Uncertainty has often been expressed as to the true nature of the luminosity in the open spaces of fluted spectra. Are they simply intervals of unshaded photospheric radiance, or is their brilliancy reinforced by the addition of bright lines? Just where they meet the black edges of the shafts of absorption, their splendour exceeds, in the opinion of some observers, what could be produced by contrast alone. It seems, nevertheless, unlikely that rays of emission should occur in these positions and nowhere else in the same spectra. Moreover, illusory impressions of the kind, both visual and photographic, are common and pertinacious. Nothing, how-

[1] *Potsdam Publicationen*, No. 14, p. 22.
[2] *Spectra of Southern Stars*, Plate iv.

ever, is more inimical to truth than dogmatic denial; we must be ready to admit much that we should beforehand have deemed impossible, even the reality of far-fetched coincidences; for anticipation is often belied by fact. Professor Keeler, whose mind was singularly free from prepossessions, found it "impossible to avoid the conclusion" that in the spectrum of *α* Herculis "the edges of the zones bordering on the dark bands are bright—much brighter, that is, than the average continuous spectrum—and that they are due to a real predominance of emission at the regions of the spectrum in which they occur. In the case," he wrote further, "of stars like *α* Orionis, of a less pure type, such a conclusion could not be safely drawn; yet the superior brightness of the spectrum at these places is obvious, and it can be traced even in second-type stars. May there not, after all, be bright regions in the solar spectrum, such as Draper supposed he had found in the places of the bright oxygen lines? And what is the relation between the dark bands in third-type stars and the bright zones which border on them?"[1]

Questions more easily asked than answered. They suggest doubts, not at once to be set at rest, as to the nature of so-called "continuous" spectra. May they not in certain cases include several maxima of radiation? The possibility is at least not excluded of individual differences in this respect between stellar photospheres. Yet of true gaseous emissions there seems to be no trace in Antarian stars. The admission of its presence could not be made for one without being extended to all; and many spectra of the class are clearly exempt from abrupt intensifications.

Chemical recognition has not been carried far in them. The familiar lines of only five substances—iron, calcium, magnesium, sodium, and hydrogen—are entirely unmistakable. The rest await more searching scrutiny. It will be of especial interest to determine whether titanium and its usual associate, vanadium, retain in these objects any share of their importance in sun-spots. Helium-absorption, too, which occasionally emerges to view in spot-spectra, might be looked for with some prospect of success, but is likely to be inconspicuous. The fundamental problem, however, in this connection relates to the

[1] *Astroph. Journ.* vol. vi. p. 424.

origin of the flutings. It ought to prove capable of a definite and, so to speak, a simultaneous solution. For the members of the system show the coherence of a structural design. They form a marshalled array, an interdependent order. Their occurrence piece-meal need not then be expected. They will be recognised together or not at all.

Stars with fluted spectra have a fixity significant of immeasurable remoteness. Yet two—Antares and Betelgeux—are of the first order of apparent brightness. Their real magnitude must hence be prodigious. An approximate estimate of it can be arrived at in the case of Antares, which has an ostensible parallax of 0·021″, corresponding to a light journey of 155 years. This, at least, was the outcome of Mr. Finlay's measurements at the Cape; but it is so small as to lie but slightly outside the margin allowed for their probable error. Its genuineness can then only be assumed for the purpose of fixing ideas; since the star may be indefinitely further off, while unlikely to be appreciably nearer, than this minute annual shift asserts it to be. Under this reserve we may compare Antares with our standard star, $\alpha_2$ Centauri, which, as we have seen, is equivalent to comparing it with the sun. The result is to show that four hundred suns, in its place, would barely supply the light we receive from the *alter ego* of Mars.[1] And this is only what remains after a heavy absorption-toll has been levied—a toll of probably twice the amount paid by the sifted solar beams. The photospheric extent of Antares may then be set down as at least eight hundred times that of the sun, while the immense sphere it covers may be held, on good grounds, to have a comparatively high mean density. Even on the basis of equality in this respect, its mass would exceed that of the sun more than 22,000 times, while gravity at the surface of this unimaginable globe must possess at least twenty-eight times its solar power. Similar reasonings apply to Betelgeux, only with still further enlargement in measure of the conclusions they lead to. For Betelgeux is a more brilliant luminary than Antares, and its immobility in the sky is, if anything, more nearly absolute.

[1] The star was named *Ant-Ares* ("like Mars") because of its resemblance to the planet in colour.

The processes of interior circulation in such bodies are extremely difficult to realise. The intensity of radiation must depend—other things being equal—upon the promptitude of delivery at the photospheric level of heated stuff from within. This must increase with the force of gravity, which is the driving power on ascending and descending currents; but it must, on the other hand, fall off as the sphere they traverse grows more compact. The manner in which the balance is struck in each individual star between these opposing influences transcends every rational conjecture. We can only see that it must vary widely, and that its variations necessarily affect the photospheric composition and the radiative characteristics of the globes in which they prevail.

Antarian stars obey no special law of distribution. They are scattered at large over the heavens, and usually in isolated positions. They show as a rule no tendency to gather into groups. A collection of nine specimens, located in the intervening space between the two grand clusters in Perseus, is perhaps unique. Discovered by Mr. Espin in 1891,[1] this nest of red stars appears like a garnet clasp linking together a pair of diamond aigrettes. They are of about the eighth magnitude, but may nevertheless, since they are assuredly vastly remote, be most majestic orbs. Not that we should ascribe to all stars of this spectral type the colossal dimensions of Betelgeux and Antares. The same degree of variety may be supposed to exist among them as among solar stars. Yet the analogy may not hold. It is conceivable that very great mass is a pre-requisite for the development of a fluted spectrum.

[1] *Monthly Notices*, vol. lii. p. 154.

# CHAPTER VII.

## CARBON STARS.

STARS of Secchi's fourth type, also known as "carbon stars," are the most exclusive of stellar families. They hold remarkably aloof from every other. They have indeed traceable relationships; but the genealogy obscurely indicated by them needs authentication.

Mr. Espin published in 1898 a catalogue of 237 carbon stars,[1] and about a dozen objects of the kind have since been detected. None are as bright as the fifth, and only seven exceed the sixth magnitude.[2] Their inconspicuousness probably arises, not from any deficiency of intrinsic light-power, but from the overwhelming absorptive action of their atmospheric envelopes. Thus only a small part of their original radiations attain to outer space; none of the shorter wave-lengths escape; the spectra are cut off short a little below the place of the blue calcium line. Intense visual redness is a consequence. These stars glow sanguine in the field of the telescope; they are variously compared to "drops of blood," to carbuncles, garnets, or rubies. By a rough estimate, 12 per cent are strikingly variable, the proportion being nearly the same as for third-type stars. Scarcely any, however, shine steadily; if attentively watched, they can be perceived to flicker and fluctuate more or less extensively.[3] Some of their changes are indeed so lasting as to suggest a permanent drop or rise (as the case may be) in the photometric scale. The circumstance that instability of light ordinarily accompanies redness of colour in stars is most curious and significant.

[1] *Monthly Notices*, vol. lviii. p. 443.

[2] *Astroph. Journ.* vol. x. p. 93.

[3] Espin, *loc. cit.*

The fundamental characteristic of fourth-type spectra is the presence of three deep bands, degraded towards the violet, sharp towards the red. They are a negative copy of the emission-bands displayed by comets. Five or six additional dusky stripes, so far unidentified, are of less distinctive construction. The general effect of these spectra differs from that of the fluted sort chiefly in two ways. First, the *columns* of absorption are broader and more massive; they are of Doric rather than Ionic proportions. Secondly, they are illuminated from the opposite direction; the chiaroscuro is inverted. Their variations of relative intensity in different objects have been proposed as subsidiary classification-marks, but cannot be much insisted upon. Such individualities—as Professor Dunér pointed out—do not imply radical distinctions; and they are so prevalent and so various that, by closely attending to them, "one might easily get as many subdivisions as there are stars." [1]

The linear spectrum in carbon stars is seen with difficulty through the cloak of the bands. It is, however, none the less important. Sodium and iron contribute to it, but most of its constituents still lack interpretation. Hydrogen and helium alike fail to appear. No calcium lines are visible; indeed those in the blue and violet, which would most naturally be looked for, could not show through the dense veil of absorption shrouding the upper spectral reaches; so that their seeming absence is consistent with the presence of a calcium ingredient in the stellar atmospheres. Their carbonaceous strata nevertheless give them their special character. No other sidereal objects, except an imperfectly observed variable star, show a trace of the cometary analogy prominent in the fourth spectral type.

The carbon bands, which constitute its leading feature, were identified by Father Secchi in 1868, and he noticed besides certain bright lines, the reality of which, long discredited, has quite recently been confirmed. He noticed them, however, somewhat confusedly, for he at times failed to keep them apart from the illusory effect of vivid emission caused by the prismatic gleaming of the intercolumnar zones. Professor Hale in 1898, effectively aided by Mr. Ellerman, applied

[1] *Astroph. Journ.* vol. ix. p. 132.

the photographic method with remarkable success to the investigation of these spectra. They offer no facilities to the camera. The use of ordinary plates is of course precluded by their deficiency in blue rays; only those rendered "orthochromatic" by suitable dyes avail for their delineation; and these are found practically inconvenient owing to irregularities in sensitiveness. A series of splendid pictures was nevertheless obtained with the aid of the Yerkes forty-inch refractor; but the arduousness of the undertaking can be estimated from the fact that, with a train of three prisms, exposures of nine hours were required to secure impressions comparable with those given by the spectrum of Betelgeux in twenty seconds.

The research embraced, to begin with, twenty-two stars, ranging from 5·4 to 8·2 magnitude.[1] Most of the spectrographs were limited to the region D to *b*; but a few extended to λ 4450, where dark blue merges into indigo, and one ranged far down in the crimson. This was derived from the brightest specimen of the type, numbered 152 in Schjellerup's Catalogue of Red Stars. Situated in Canes Venatici, it shows a spectrum of such rare beauty as to justify the title of "La Superba," bestowed upon it by Secchi in 1868. Its yellow section, photographed by Hale, is shown in Plate XI. Fig. 2. A surprising amount of detail is imprinted in it. On the original negatives over a hundred lines were measured where no more than three or four had been previously recorded.[2] Most of them are dark, but some are bright, among which, apparently, may be reckoned two yellow rays, compared by Secchi to "exquisite threads of gold." They are prominent in our figure at wave-lengths λ 5593 and λ 5693, which, as Professor Hale was careful to point out, "agree very closely with" those of "two bright lines in the spectra of the Wolf-Rayet stars."[3] He adds the caution that, several other similar approximate coincidences notwithstanding, "it is too soon to conclude that these classes of stars are related." A fine group of vivid green lines was also photographed, and some blue rays were

[1] *Astroph. Journ.* vols. viii. p. 237, ix. p. 271, x. p. 87.

[2] Hale, *First Annual Report*, p. 7. Spectrographs of 152 Schjellerup, taken by McClean with two hours' exposure, were described by him in 1897 as showing a multitude of dark lines.—*Monthly Notices*, vol. lvii. p. 8.

[3] *Astroph. Journ.* vol. viii. p. 239.

suspected. Although intensely red, 152 Schjellerup has not been observed to vary from 5·5 magnitude.

The typical star of Miss Maury's "Group xxi." is 19 Piscium. It shows a splendid four-zoned spectrum, vivified by the twinkling of emission rays (see Plate XII. Fig. 2). Secchi noted in it the shining of the same "threads of gold" previously seen in 152 Schjellerup,[1] and they may be considered as a feature common to all spectra of this class. The opinion to this effect expressed by M. Dunér carries great weight. It was in 1884 entirely adverse to the reality of the bright lines recorded by the Roman astronomer;[2] but he changed his view on improving his instrument. The materials for his invaluable Memoir of 1884 were collected with the Lund ten-inch refractor; in 1893 a Steinheil of fourteen inches aperture became available to him at Upsala. With it he at once undertook a revision of his former work,[3] which, although hampered by serious interruptions, progressed steadily down to 1898. M. Dunér was not disappointed in his hopes of seeing more and better with the larger instrument; and he chronicles as of primary importance "the fact that he was able to detect without difficulty bright lines in various spectra, which at Lund were either invisible, or at least could not be discovered." Professor Hale's photographic registration of them was thus visually authenticated by an observer of unrivalled experience, and was further verified with the great Lick telescope by Professors Keeler and Campbell under conditions so admirable as to leave little or no room for surviving doubts.[4]

It may then be regarded as an established fact that spectra of the fourth type include elements of direct emission. They are subsidiary, yet distinct, and seem to be unfailingly present in all members of the class. Three characteristics may provisionally be ascribed to these curious bright lines. In the first place, they are of entirely unknown origin. Hydrogen and helium are equally (so far as published measures enable us to judge) alien to their production. Some of them may coincide with Wolf-Rayet lines, but if so, it is with

[1] *Sugli Spettri Prismatici delle Stelle Fisse*, Mem. ii. 1869.
[2] *Sur les Étoiles à Spectres de la Troisième Classe*, pp. 10, 82.
[3] *Astroph. Journ.* vol. ix. p. 119. [4] *Ibid.* vol. x. p. 110.

Wolf-Rayet lines which themselves lie outside the range of terrestrial acquaintanceship. Not even the exotic light of nebulium or coronium can be seen to glimmer in carbon stars. Secondly, they are independent of luminous change. They do not betoken variability. They occur indifferently in objects of steady lustre and in those subject to wide vicissitudes. Nor has the slightest sign of inconstancy been detected in the rays themselves. They do not fade and flash capriciously or periodically. They shine equably—to all appearance—from year to year, and from decade to decade. Thirdly, the locus of their development is above the region of carbon absorption. The tinted rays evidently overlie the dark bands; they are seen projected upon them. The substances to which they are due must then be found at a higher level in the stellar atmospheres than the carbon vapour. As Professor Hale remarks,[1] the case is paralleled in the sun, where hydrogen and calcium rise to great heights, while a shallow layer of carbon-gas lies low at the base of the chromosphere. This arrangement of emissive and absorptive strata does not prevail—as we shall see later—in stars of all spectral classes. They are, on the contrary, markedly distinguished in this respect, and the distinction implies profound physical differences.

It was found possible at the Yerkes Observatory to form a sequence of eleven stars,[2] in the order of growing depth of carbon absorption (see Plate XII.). The transition from one of these objects to the next was so gradual as to suggest that they represented actual phases of development. This, however, is merely a convenient hypothesis. One of the earliest of the series is unique, according to Dunér, in the relative strength of its spectral bands. Those due to carbon are quite feeble, while one of untraced origin in the red is broad and black. This star, known as 280 Schjellerup, is scarcely brighter than the eighth magnitude, so that it can be dealt with to advantage only by the aid of powerful instruments. Passing on to 19 Piscium, we find *one* of the three carbon bands dim, the others—in the green and blue respectively—very wide and dark. Their unequal prominence constitutes a striking

[1] *Astroph. Journ.* vol. x. p. 112.
[2] *First Annual Report*, p. 8.

anomaly. It recalls the variations in relative brightness of the hydrogen lines recorded with surprise in nebulæ and sundry species of stars.

A spectrum intermediate between those of 19 Piscium and of 152 Schjellerup is shown by the variable star U Hydrae (132 Schjellerup.) Dunér noticed long ago the wonderful chromatic effect of its four brilliant zones,[1] set off by deep bays of absorption; and Secchi perceived in it a green, as well as a yellow pair of fine rays, the genuineness of which is more than probable. The star fluctuates irregularly from 4·5 to 6·3 magnitude, but is very rarely seen at its maximum brightness. Professor Hale's spectrographs afforded evidence of a partial but very interesting resemblance between its spectrum and that of $\mu$ Geminorum, a fine example of the fluted description, and the agreement—as can be seen by inspecting Plate XV.—extends to the sun. "Further toward the red," he tells us,[2] speaking of the banded varieties, "the spectra become very unlike, though even here there are certain important points of resemblance which must be carefully investigated." Only their linear elements are naturally in question; the shadowing bands are totally unlike in the two classes. The coincidences detected, however, are of real importance as forging a link, even if a slight one, between stellar families that stood previously entirely apart.

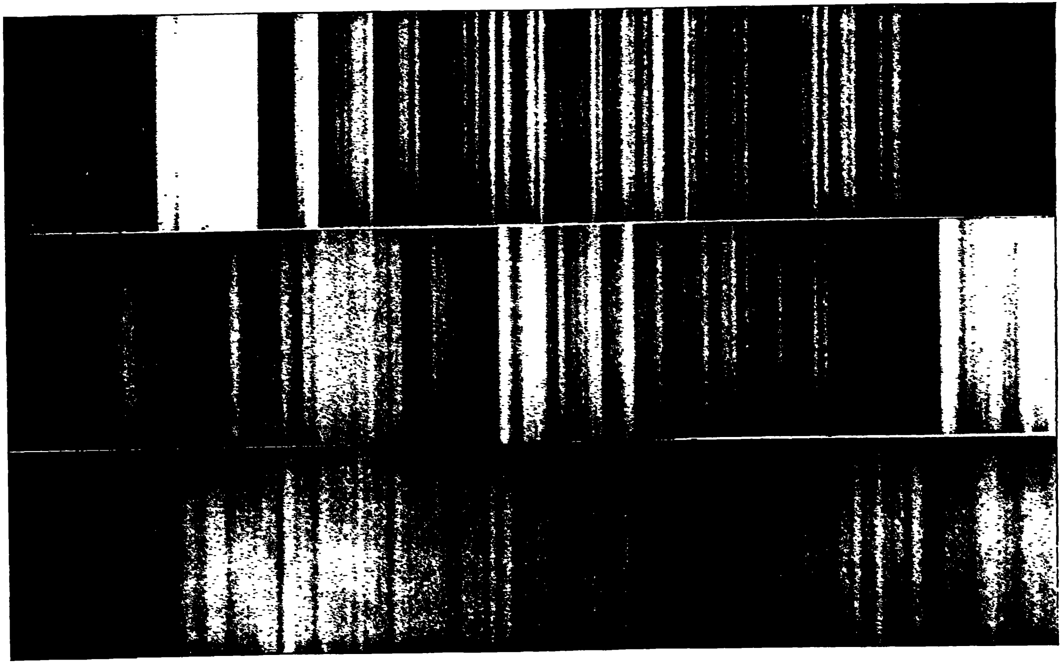
The invisibility (up to the present) of hydrogen in carbon stars is not easily accounted for. The substance must enter into their composition; its diffusion is seemingly universal and profuse; why, then, is its manifestation, whether by emission or by absorption, suppressed in this particular class of objects? The same query may be put in regard to comets, and the same obvious, although perhaps insufficient answer presents itself, namely, that their stock of hydrogen has been consumed in the fabrication of hydrocarbons. It is worth noting besides that the only metals yet identified in these stars—sodium and iron—are precisely those perceived to glow in one or two exceptional comets. But this may be only a chance concurrence.

The rule of colour in carbon stars long seemed inviolable;

[1] *Sur les Étoiles*, p. 45.

[2] *Astroph. Journ.* vol. ix. p. 274.

1.
2.
3.



Spectra of Stars of Types II., III., and IV. (Hale and Ellerman).

1. The Sun (Type II.). 2. $\mu$ Geminorum (Type III.). 3. 132 Schjellerup (Type IV.).

yet there are exceptions to it. Two spectra of the kind well extended in the blue were photographed at Harvard College in 1891, and they belong, in fact, to white stars.[1] They are situated, one in Aquila, the other about three degrees north of $\epsilon$ Ceti, and are of the seventh and eighth magnitudes respectively. Their investigation ought to prove peculiarly instructive, for in them the type has developed under most unusual conditions. It is besides more completely exhibited. Sections of these spectra can be registered and examined which in other analogous objects are concealed by dense general absorption. It should, for instance, be possible to determine whether calcium lines are really or only apparently absent from fourth-type spectra.

Carbon stars, there is little doubt, are inordinately distant from the earth. None, we believe, have any measurable proper motion, and experiments on their annual parallaxes would certainly prove a waste of time and trouble. We have, then, no means of estimating their real brilliancy, but it *must* in some cases, and it *may* in all cases, be exceedingly great. These objects show a marked preference for the Milky Way.[2] They occur, however, in other parts of the sky as well. They are condensed towards the galactic plane, but not limited to it. They are unmistakably, yet far from exclusively, swayed by its attraction.

[1] They are catalogued in the southern zones of the Bonn Durchmusterung as $-10°5057$ and $-10°513$.

[2] Hale, *Astroph. Journ.* vol. viii. p. 239 ; Espin, *ibid.* vol. x. p. 170.

## CHAPTER VIII.

### STARS WITH FLUTED SPECTRA SHOWING BRIGHT LINES.

ALTHOUGH the display of bright lines in fluted spectra is a sure sign of extensive variability, it is not the light-changes of the stars thus characterised that here concern us. The two classes of phenomena are beyond question intimately related; but as a matter of pure convenience they have to be treated of apart.

Mira Ceti has the advantage over its fellows of rising to more brilliant maxima, and of having received longer attention and more careful study. Since, however, all the members of Class vi. are not copied from one pattern, investigations conducted too exclusively can only lead to partial knowledge; and, indeed, the varieties distinguishing the different specimens are precisely their most instructive feature. Thus they agree in showing *some* brightened hydrogen lines, but not in the selection of those to be brightened. Then helium rays are vivid in certain of these stars, dark in others, and there are further, less assured diversities. These cannot yet be explained by any single consistent theory, but they may be definitely ascertained and brought into some kind of orderly relationship.

The spectrum of Mira has a prescriptive right to be considered first. It is the model, deviations from which count as exceptional. The bands are profound, the radiations of hydrogen intense during fully one-third of the light-period of eleven months. Detected photographically at Harvard College in 1886, they are now looked for, and rarely missed, in every analogous object as it rises from quasi-extinction. The hydrogen stratum in Mira seems to be in a peculiar condition. It emits only the higher members of the Huggins

series, the red and the green lines (C and F) being alike invisible. The blue and the indigo lines, on the other hand, shine with extraordinary brilliancy—a brilliancy "too great to be shown on a drawing or to be safely expressed by a number representing relative intensity"[1] (see Plate XIII. Fig. 1). The fifth hydrogen line, by a rule without exception in Mira variables, is hidden; but eight of its associates in the ultra-violet have been recorded. Very singular, indeed, is the partial presentation in this star of a closely-linked sequence of vibrations. It can hardly result from an extraordinary elevation of temperature; we can better conceive it as due to some subtle form of electrical action not yet evoked in the laboratory. The state of things as regards the hydrogen spectrum is the opposite of that prevailing in the reversing stratum of the sun. Here the upper radiations are suppressed; in Mira the series starts from its third term.

The star has been spectrographically investigated by Vogel, Sidgreaves, and Campbell. The Potsdam plates were exposed during the low maximum of January-February 1896,[2] when the variable scarcely exceeded fourth magnitude; and this is a circumstance to be borne in mind, since there is reason to suspect that emission may differ, not only in degree but in kind, at light crises of different intensities. However this be, *only* the hydrogen lines were perceptibly vivified in 1896. Of the dark lines measured by Dr. Vogel, many coincided with Fraunhofer rulings, but a goodly proportion seemed unfamiliar.

The maximum of 1897-98 was studied by Father Sidgreaves.[3] It was an improvement upon that observed by Vogel. Mira attained 3·2 magnitude on 30th November. The Stonyhurst plates were isochromatic; their range of sensitiveness extended from high up in the violet to near D in the yellow, and they continued to be exposed until 5th February, when the variable had sunk to the sixth magnitude. But the light remained essentially unchanged in quality, although reduced to one-thirteenth its original amount. Only the continuous spectrum in the blue had faded, relatively as well as absolutely, showing that the star grew redder in its decline.

[1] Sidgreaves, *Monthly Notices*, vol. lviii. p. 345.
[2] *Sitzungsberichte*, Berlin, 26th March 1896.
[3] *Monthly Notices* vol. lviii. p. 344.

Professor Campbell's[1] observations at the maximum of October 1898 had the two-fold advantage of being made with a magnificent apparatus and at an exceptionally bright phase. In more ways than one they mark a beginning. They both suggest relations and establish facts. The plates exposed with the Mills spectrograph attached to the great Lick refractor show only the region near the third hydrogen line ($H\gamma$) in the fine detail needed for measures of precision. These were designed primarily for the determination of the star's radial movement, which proved to be one of recession at a speed of 62 kilometres ($38\frac{1}{2}$ miles) per second. It may be regarded as constant. No part of it seems to be due to orbital motion round an invisible companion. It was, however, derived exclusively from the *dark* lines in the spectrum. The *bright* lines told a different tale. Four were compared—a hydrogen pair and a pair ascribed to iron—and all showed a much smaller displacement redward than the dark lines. The amount of the discrepancy, moreover, proved subject to fluctuations; but to fluctuations obviously depending upon intrinsic, not upon extrinsic causes. No attempt has been made to explain them on the hypothesis of variable motion. It may be accepted, on the evidence of lines physically in a normal state, that Mira—so far as appears yet—is a solitary body in course of withdrawal from the earth at a uniform rate of 38 miles a second.

Early in October 1898 the star reached 2·6 magnitude, and during the few weeks of its greatest brightness the blue and indigo hydrogen bands were perceived to be broken up each into three unequal components. This remarkable appearance falls into line with symptoms of disturbance in stellar spectra of other types, but had not previously been observed in a Mira variable. It is of very curious interest. In studying the "intensity curves" of the tripled line (see Fig. 19) the conviction becomes almost irresistible that here a "Zeeman effect" is in question. The polarisation test might decide. If the lines are distended and shattered by powerful magnetic action, then the lateral components and the central component must be polarised in planes at right angles to one another, and the rotating of a Nicol's prism in

[1] *Astroph. Journ.* vol. ix. p. 31; *Observatory*, vol. xxii. p. 152.

the field should produce alternating extinction. Professor Campbell was prepared to make the experiment at the maximum of 1899, but the star unfortunately failed to replenish its due measure of light, and gave an imperfectly legible spectrum. Favourable opportunities, however, for applying this simple criterion must frequently recur, and they are well worth watching and waiting for. Positive results of the kind indicated would be of revolutionary importance; obscure phenomena would be illuminated; anomalies would be removed; a boundless region would be thrown open to

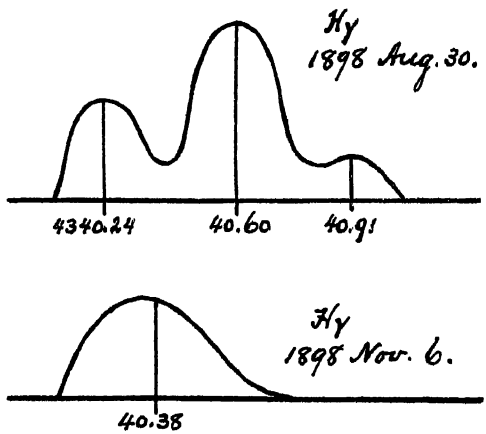



FIG. 10.—Intensity-Curves of Hγ in Spectrum of Mira (Campbell).

investigation. The issue, it is scarcely too much to say, is vital to the progress of astrophysics.

The production of multiple hydrogen-lines in the spectrum of Mira may quite possibly be restricted to brilliant phases. Metallic emission almost certainly is. Thus the iron rays (λλ 4376, 4308) registered as bright in 1898 were, the one strongly dark, the other either dark or invisible in 1896 and 1897. This gives a hint of the diversities to be looked for in the future, and lends enhanced interest to minutiæ of observation which in themselves might seem trivial.

The spectrum of Mira includes a good many dark lines closely adjacent to, if not actually coincident with, rays of helium. None have been seen bright. Calcium absorption is

very prominent. The line in the blue, which develops with increase of pressure, comes out as a black grooving; the giant pair in the violet are of surprising intensity. The less refrangible, as in all such stars, smothers the hydrogen emission of nearly its own wave-length; and this circumstance demonstrates some unexpected relations. The calcium-layer, plainly under considerable pressure, must be located, as in the sun, quite close to the photosphere. But the glowing hydrogen necessarily lies lower still, stoppage of light implying superincumbence of the arresting vapour, and there seems no room for it except in the very interstices of the photosphere itself. The overlaying of a light by a heavy substance is indeed anomalous, yet no other arrangement is consistent with the spectral phenomena of Mira and its congeners. Besides calcium, iron, magnesium, strontium, titanium, manganese, and chromium are easily recognised as absorptive constituents of its atmosphere.

The mode of hydrogen-radiation characterising Mira does not recur in all stars of its type. Some show the two lowest lines conspicuously bright, and they are often accompanied by the glimmering of the yellow helium ray. R Aquilæ is an example.[1] Other members of the class have F for their chief bright line, C being invisible, as in R Andromedæ and S Cassiopeiæ, or dim as in V Boötis. Hydrogen in these stars appears to exist in its nebular condition.[2] Analogous to them in some respects, R Cygni may in others be divergent. Its chief bright lines are F and D;[3] but the nature of the accompanying banded absorption appears somewhat indeterminate.[4] It might be definitely ascertained by a few well-timed observations. An important spectrographic investigation of $\chi$ Cygni was carried out by M. Eberhard at Potsdam in 1901.[5] It disclosed phenomena closely analogous to those detected by Campbell in Mira. Thus the maximum of lustre was attained, in the hydrogen series, by its fourth member ($H\delta$); iron lines, both bright and dark, were abundantly visible; above all, the absorption and emission-spectra were relatively displaced, just

[1] Krüger, *Astroph. Journ.* vol. ii. pp. 151, 158.

[2] Keeler, *Lick Publ.* vol. iii. p. 225.

[3] Espin, *Astr. Nach.* No. 2859.

[4] Maunder believed it to be of fourth type, 1st Oct. 1888. *Monthly Notices*, vol. xlix. p. 303.

[5] *Astr. Nach.* No. 3765.

as in Mira in 1898. The bright lines, that is to say, were pushed towards the blue, while the dark lines deviated in an opposite sense, though very slightly, from their normal places. This surprising feature may then prove common to the whole of this class of stars, and doubtless depends upon some essential peculiarity of their constitution.

About two hundred variable stars with fluted spectra are known to emit bright lines, and this kind of spectrum is a distinctive badge of variability. Mrs. Fleming's classification of them[1] is based mainly upon differences of hydrogen-emission. For the typical star of the first of her eleven groups she chose R Lyncis, in which $H\beta$ and $H\gamma$ are brilliant, while $H\delta$—sometimes the brightest line in Mira—is scarcely visible. She then traced a continuous sequence of change to R Leonis, the exemplar of her last group, in which $H\beta$ is imperceptible, $H\gamma$ excessively faint, $H\delta$ conspicuous. But this order of relative lustre is not in R Leonis permanently maintained. The effacement of the green ray is only transient. In April 1895 Dr. Krüger, observing with the eleven-inch Bamberg refractor, found it to dominate the spectrum; and MM. Gruss and Laska saw in the same star, 6th May 1894, $H\alpha$ doubtfully, $H\beta$ and $D_3$ unmistakably, although two nights later $H\alpha$ shone alone, while on 28th May $H\beta$ was similarly isolated. Such changes, inexplicable as they are, cannot be set aside as incredible. Their further investigation is most desirable. Meanwhile, the relative brilliancy of the hydrogen lines in variables evidently supplies a highly insecure basis for their arrangement.

Mira is the only member of its family which has been at all adequately studied. A good beginning has been made with $\chi$ Cygni; but about most of the remaining couple of hundred, particulars are wholly lacking. The great majority, having been registered in sweeping spectrographic surveys, were pigeon-holed for future reference, after brief inquiry into the history of their recorded light-changes; and in their pigeon-holes they have been mostly allowed to rest. Enough is known, however, to whet curiosity as to what remains unknown. Spectral changes of a remarkable kind affect these stars; their thorough verification and the unravelment of

[1] *Astroph. Journ.* vol. viii. p. 233.

their tangled relationships are essential to progress. The work may be difficult, but it is of profound interest. The elucidation of the hydrogen-spectrum in one variable star may indeed open the door to unexpected and far-reaching discoveries.

The helium-spectrum is equally significant, but more evasive. The emergence of the yellow ray seems to accompany the brightening of the two lower hydrogen rays; but its shining may be comparatively transient. The important point, however, is that it does not seem to occur at all in stars showing, like Mira, a mutilated hydrogen series. Then there is the further question whether $D_3$, when it does shine out, shines alone. Are all its numerous associates invisible, or are they dark, as some of them appear to be in Mira? Finally, we know very little as yet about the lighting-up of metallic rays in such spectra. It is nevertheless certain that some regulating principle governs the selection of those brightened; and only by detailed study can the nature of that principle be ascertained. All this, and much more, needs prolonged and extended inquiry; but in a field that will yield ample return for the expended labour.

# CHAPTER IX.

## HELIUM STARS WITH BRIGHT LINES.

TEMPORARY stars, and a few stars variable in short periods, belong, properly speaking, to this class; but for the sake of clearness and convenience, they are reserved for separate treatment. The question of light-change will demand later on our undivided attention; it bristles with difficulties, which we are not at present prepared to encounter.

Alcyone, the chief Pleiad, long passed for an ordinary Orion star. Dark lines of hydrogen and helium were prominent in its spectrum; there seemed no reason to suspect the slightest deviation from normality. Nevertheless, Campbell perceived in 1893 [1] the red radiance of C set off by a narrow dark line on its more refrangible side; and this state of incipient emission appears to be permanent.[2] Alcyone might then be counted a linking instance between Classes i. and vii. The discovery was startling that a single substance could show certain of its rays bright, the remainder dark, in one and the same star. But the fact, although highly perplexing,[3] has become so common to experience as to have ceased to be surprising. Examples of its occurrence have been registered by the score as regards both hydrogen and helium. They are all found in Classes vii. and viii. (bright-line helium and Wolf-Rayet stars); Mira-variables seem never to have their hydrogen spectrum thus conditioned. Professor Campbell [4] noticed it as

[1] *Astroph. Journ.* vol. ii. p. 178. [2] Runge, *Astr. Nach.* No. 3471.

[3] Professor Frost's conjecture that such stars may possess atmospheres preferentially absorbent of the shorter radiations did not seem to himself plausible enough for publication. *Astroph. Journ.* vol. ii. p. 182. A similar explanation, however, has lately been recommended by Dr. Kayser. *Ibid.* vol. xiv. p. 313.

[4] *Astroph. Journ.* vol. ii. p. 181.

an invariable rule that the bright lines in Orion stars "are those of greater wave-length," while "the dark lines are those of shorter wave-length."[1] This applies also to helium, but in a qualified sense. If all the lines in its spectrum are taken indiscriminately, the bright and the dark appear to succeed each other without method; but their consideration by series makes it at once evident that, within the limits of each set of vibrations, the bright members are invariably fundamental. This is important, not only for the better ordering of stellar phenomena, but as regards the theory of spectral series in general.

In Alcyone, then, emission is at a minimum; it could scarcely diminish and remain existent. And it is quite possible that it may be on the wane; after the lapse of some hundreds, or thousands of years, the chief Atlantid will perhaps have lost the distinctive note of its spectrum, and will have sunk to the level of unrelieved absorption. One of its companions at present stands out from the crowd in the same way, but more decidedly. Pleione shows three hydrogen lines pretty strongly bright, and they are inevitably C, F, and H$\gamma$. Centrally superposed upon wide dark bands,[2] they assert by this fact alone the non-correspondence in position of their originating stratum with the glowing hydrogen in stars like Mira. And this teaches us the important lesson that there is no stereotyped recipe for the production of stellar bright lines, but that they may originate diversely in the various spectral classes.

The Pleiades are nebulous collectively, and in many cases individually as well; but they are less closely folded in nebular swaddling-bands than the group of stars forming the nucleus of the great Orion nebula. It consists of four leaders, of about the fourth, fifth, sixth, and seventh magnitudes respectively, two of which have faint companions; and, scattered promiscuously, there are to be found besides four minute stellar points, detected at Lick by Professor Barnard and Mr. Alvan G. Clark. For spectroscopic purposes the "trapezium," or quartette of bright stars, may be treated as one, since they

[1] Evidently analogous is Hale's result that the lines first reversed in metallic spectra are the most refrangible. *Astroph. Journ.* vol. xv. p. 227.

[2] A. C. Maury, *Harvard Annals*, vol. xxviii. p. 104.

shine with sensibly the same quality of light, while their scarcely visible associates give radiations negligible in amount. Most difficult questions arise in attempting to decide upon the true nature of the trapezium-spectrum. The prevalent view at first was that the stars were of the ordinary dark-line helium type, bright lines coming in here and there simply as projections from the enormous volume of gaseous stuff interposed between the eye and the stellar nucleus of the formation. But the opinion was grounded on superficial evidence, and has not held its ground. Some lines, bright in the nebula, *refuse* to cross the thin strip of continuous light due to the star; they stop short on one side of it, and reform on the other,[1] the two sections being divided by a narrow gap of absorption. This proves that the nebular rays do not in all cases show bright against the background of continuous stellar light. The very strongest may do so; but it is just possible that in them the appearance is illusory, and due to a kind of irradiation.

There can, on the other hand, be no reasonable doubt that the trapezium-stars have bright lines of their own. But they are peculiar, and peculiarly conditioned. A spectrograph taken by Sir William and Lady Huggins, 5th February 1888,[2] proved to be crossed in the ultra-violet by at least four groups of fine, faint, bright lines, derived primarily from two stars of the trapezium, but extending, through their influence, as it were, some little way into the adjacent nebula. Their origin is problematical; they have not been recorded elsewhere;[3] they have been only partially verified on later Tulse Hill plates. Yet the original negative survives, and its examination has convinced several experts of the reality of the curious script read from it. Conviction, however, on such a point is apt to share the dim character of gloaming phenomena —phenomena on the border between the seen and the not seen.

But there is more. With refined apparatus the same observers succeeded, in 1894 and subsequently,[4] in separately

[1] Keeler, *Astr. and Astrophysics*, vol. xiii. p. 486. The helium line, $\lambda$ 4472, is specially described. It is bright in the Orion nebula, dark in all Orion stars.

[2] *Proc. Royal Society*, vol. xlvi. p. 41.

[3] Campbell, *Astr. and Astroph.* vol. xiii. p. 397.

[4] *Comptes Rendus*, 11th Oct. 1897; *Astroph. Journ.* vol. vi. p. 322; *Atlas of Spectra*, p. 138.

photographing three of these remarkable spectra, and they were now perceived to be rich throughout in bright and dark lines, "with the special character strongly marked of bright bands associated with corresponding dark absorption lines." Most singular of all, the relative positions of these bright and dark lines were found subject to change. Hydrogen radiations, for instance, which in 1894 lay on the blue sides of the absorption stripes, lay in 1897 on their redward margins. This might be explained on the hypothesis of orbital movement by supposing each star of the trapezium composed of a dark-line and a bright-line member, the spectra of which are periodically shifted through the alternations of their velocities in the line of sight. It remains to be seen, however, whether or not the shiftings are periodical; for by this one condition the explanation stands or falls.

So far as their absorption-elements are concerned, the stars of the trapezium belong to the earliest variety of the Orion type. All the lines are wide and diffuse, and the strongest are members of the Pickering series of hydrogen. Rydberg's series—if we may call it so under reserve—is represented by the prominent reversal of its solitary ray at $\lambda$ 4689. Mr. McClean recognised oxygen absorption in these stars; Sir William and Lady Huggins identified nitrogen, silicium, and titanium, and the calcium K shows both bright and dark. Few sidereal objects combine so many points of interest as the multiple star at the heart of the great nebula. The origin and meaning of the throngs of delicate rays, here just tantalising vision, pressingly invite research; nor less the manner of relative displacement exhibited by the bright and dark coupled lines. Do they betray a circulatory period? And if so, is it the same for each member of the group? Or do they rather form independent systems, in subordination to a higher scheme, completing itself in the long leisure of many millenniums? Other problems suggest themselves in immediate connection with these stars; nor is it impossible that they may be proposed over again, perhaps in a modified form, by the multiple stellar nucleus of the Trifid Nebula in Sagittarius. But instruments of no insignificant light-power will be needed for the satisfactory examination of its spectrum.

In one other star besides θ Orionis, the shifting of bright hydrogen lines occurs irrespectively, to all appearance, of binary revolution. Spectroscopic duplicity was at first naturally attributed to 11 Monocerotis when its peculiar character disclosed itself on the Harvard plates. Thus in the years 1888-90 the dark F of hydrogen had an illuminated border lying redward; it was on the blue side in 1891-92.[1] We are not informed whether it has since changed its position; but any attempt to impose a period upon alterations so spasmodical would evidently be hopeless. Like θ Orionis, 11 Monocerotis (=Σ 919) is compound. It consists of three stars of about fifth and sixth magnitudes, which have maintained a strict relative immobility since Herschel divided them in 1781. Their spectra, photographed as one by Pickering, were separately examined by Campbell in 1894.[2] He found two of them to include the brilliant red ray of hydrogen, while it was absent from the third. Presumably, then, only two of the trio are bright-line stars, and it may be that in these two, significant differences in the mode of emission will be brought to light by detailed and systematic investigation.

The swing of the bright lines observed in θ Orionis and 11 Monocerotis is extremely uncommon. In general, a fixed arrangement prevails, and it is of two alternative varieties. Either the bright lines centrally divide broader dark bands, as in γ Cassiopeiæ, or the bright and dark lines are bracketed in pairs, the bright below, the dark above, as in P Cygni.

Father Secchi's notice of γ Cassiopeiæ as a gaseous star goes back to 1866. He noticed the vividness in its spectrum of C, F, and $D_3$, but the helium line has not since held its own with the others. It is subject to prolonged extinctions; nor is it certain that even the hydrogen rays always keep up the same standard of brightness. The variability of the spectrum will, however, be discussed later in connection with other similar instances; here we have to do with its fundamental characteristics. The hydrogen lines in γ Cassiopeiæ are doubly reversed.[3] Wide absorption bands are divided by

[1] A. C. Maury, *Harvard Annals*, vol. xxviii. p. 104.
[2] *Astroph. Journ.* vol. ii. p. 180.
[3] A. C. Maury, *loc. cit.* pp. 49, 100.

narrower emission bands, and these again by hair-lines of darkness. Their structure is analogous to that of H and K in the solar spectrum. The radiations fall off in intensity—as Campbell's rule prescribes—with diminishing wave-length, while the absorptions gain in the same proportion. F is "superlatively bright";[1] H$\epsilon$ is neutral; no bright lines have been photographed in the ultra-violet. The helium lines are dark, with occasional exceptions; but the green and blue magnesium lines shine by direct emission, and Father Sidgreaves recognises as a probable vanadium line a strong dark-blue ray ($\lambda$ 4586), which seems to fluctuate in brightness. Another remarkable circumstance relating to this star is the recent effacement from its spectrum of the signs of sodium absorption formerly visible in it. They have, at any rate, escaped notice since Von Konkoly's record of 15th September 1884.[2] But the immense vogue and value of spectrography have tended to reduce to a minimum the attention bestowed upon the lower spectral sections, and thus unduly to incline the balance of observation. The study of $\gamma$ Cassiopeiæ might alone furnish a not inadequate task for a well-equipped observer. Only individual enthusiasm is likely to deal successfully with the baffling problems it presents. Spectral variability is, in its case, accentuated by perfect photometric constancy. The star is steadily of 2·3 magnitude. It is purely white in colour, lies immersed in the Milky Way, and has no measurable parallax. Its real size and splendour are then inestimably great.

The spectrum of P Cygni is not known to vary, although the star itself was reckoned a "Nova" on its discovery by Janson in 1600, and by its capricious emergences earned from Huygens, half a century later, the title of the "*revenante* of the Swan."[3] Finally, it settled down to fifth-magnitude brightness, which it seems disposed indefinitely to retain. Its spectrum shows an approximately complete set of bright and dark hydrogen and helium rays; but in their arrangement into couples *juxtaposition* replaces *superposition*—that is to say, the bright lines are in their normal places,[4] while

[1] Sidgreaves, *Monthly Notices*, vol. lix. p. 506.

[2] *O Gyalla Beob.* Bd. vii. p. 14. For Keeler's failure to perceive D-absorption see *Publ. Pacific Society*, vol. i. p. 80.

[3] *System of the Stars*, p. 70.

[4] Bélopolsky, *Astr. Nach.* No. 3603; *Astroph. Journ.* vol. x. p. 319.

the corresponding dark ones are shifted upward, as if by rapid motion, towards the eye. But there can be no real question of motion, since the relation persists without change year after year. Nor can it be explained on the pressure-principle of altered refrangibility. The action, if exerted at all, would be of the opposite kind to that observed. The displacements in the spectrum of P Cygni are towards the blue; if due to pressure, they should be towards the red. The phenomenon of the relative displacement of bright and dark lines in the same spectrum is one of the most interesting in stellar physics, and has received, up to the present, no adequate explanation.

The absorption lines in P Cygni are much sharper and narrower than in $\gamma$ Cassiopeiæ. Those of calcium, magnesium, and sodium are at once apparent, and Bélopolsky ascribes many of the remainder to nitrogen.

The spectrum of the great southern variable, $\eta$ Carinæ, resembles that of P Cygni by its inclusion of many bright lines shadowed by dark ones on their blue sides. It has been photographically studied by Sir David Gill, Mr. McClean, and Miss A. J. Cannon.[1]

Among stars nearly related to $\gamma$ Cassiopeiæ may be mentioned $\phi$ Persei (4·2 magnitude), $v$ Cygni (4·4 magnitude), $\alpha$ Columbæ (2·7 magnitude), $\delta$ and $\mu$ Centauri (2·8 and 3·4 magnitude). Bright F was detected by Mr. Espin[2] in the spectrum of the star in Perseus, and was found by Campbell[3] to be accompanied by a much brighter C. The total absence of K is surprising, but may not be permanent if the spectral variability suspected at Potsdam[4] be substantiated. In $v$ Cygni there appear to be double reversals of helium as well as of hydrogen.[5] Of $\alpha$ Columbæ it is only known that F is a broad dark line bisected by a narrow bright one. The spectra of the two stars in Centaur are thought to be almost identical.[6] Hydrogen emissions in them are strong and numerous, but none others have been recognised. The helium lines are all dark; metallic lines are inconspicuous.

Bright hydrogen and helium lines seem like relics of past

[1] *Harvard Annals*, vol. xxviii. p. 175. [2] *Astr. Nach.* No. 2963.
[3] *Astr. and Astroph.* vol. xiii. p. 158.
[4] Frost, *Astroph. Journ.* vol. x. p. 365. [5] A. C. Maury, *loc. cit.* p. 104.
[6] McClean, *Proc. Royal Society*, vol. lxii. p. 419.

conflagrations. In a few cases we know them to be such, and it is possible that in all they have the same implications. For any of these stars may have undergone prehistoric vicissitudes of lustre, after which they would have settled down into stability; although the recurrence of such incidents in the future can alone afford secure grounds for inferring that they diversified stellar biographies in earlier times. Bright-line helium stars are for the most part situated in the Milky Way. They are subject to the influences exercised by that strange aggregation.

# CHAPTER X.

## WOLF-RAYET STARS.

A VERY remarkable star was described by Professor Pickering in 1896.[1] Through the measurement of its absorption lines a companion hydrogen series to that already known was, for the first time, recognised; while both the Wolf-Rayet bands in the azure showed in it by direct emission. Only the presence of a dark K obliges us to separate $\zeta$ Puppis from Wolf-Rayet stars proper, and to consider it as a linking instance between them and helium stars of the earliest variety. Just this trace of calcium-absorption differentiates the hybrid spectrum of the star in the Poop from spectra of Class viii., which include no legible metallic impressions. Their absence is of especial importance as extending to nebulæ. Nebular chemistry is entirely non-metallic.

The Pickering series in Wolf-Rayet stars is not infrequently bright in its lower members, submerged by absorption higher up. The bands in the blue, on the other hand, are always bright. They form a multiple group, the mutual relations of which await more complete disentanglement. The lowest member is, or may be, the "fundamental" of Rydberg's hydrogen series at $\lambda$ 469. Yet the circumstance that it is not really solitary tends to discountenance this identification.[2] The "lazulite" ray at $\lambda$ 465 is never entirely effaced, and Campbell has provided it with several associates of still shorter wave-lengths.[3] Some of these fall suspiciously near nitrogen lines. The possibility is not then excluded that all these

[1] *Astroph. Journ.* vol. iv. p. 369. For a list of analogous objects see *Observatory*, vol. xxii. p. 54.

[2] *Observatory*, vol. xxii. p. 52.

[3] *Astr. and Astroph.* vol. xiii. p. 467.

enigmatical blue effluences may be the joint products of glowing hydrogen and nitrogen, although this view, like every other that can be proposed, is beset by serious difficulties. Among the less refrangible of the Wolf-Rayet bright lines there are two (at about λ 569 and 559) which appear to coincide with rays photographed by Professor Hale in carbon stars. Neither has been chemically interpreted. One of them, the greenish or "citron" line (λ 569), seems in some way correlated with the blue band at λ 465. A more definite connection can be traced between the latter and the yellow line at λ 581. They are emphasised in the same stars, while the brilliancy of the Rydberg beam at λ 469 is accompanied by a special vivifying of the green Pickering line at λ 541. This rule is quasi-universal; it may stand, at least temporarily, as a useful principle of order amid half-intelligible phenomena.

Hydrogen is most diversely imprinted on the Wolf-Rayet spectra. Its lines, according to Professor Campbell, "have nearly every known character. In many of the stars they are dark. Again, they are dark with bright borders, and suggest strongly that they are doubly reversed. The bright hydrogen lines vary from faint to very bright, from monochromatic lines to very broad bands, and from those clearly single to those apparently multiple." This splitting-up of widened lines is evidently analogous to the tripling of the brilliant hydrogen rays observed in Mira, and once more recalls the possibility that certain peculiar stellar spectra may be produced in powerful magnetic fields. Helium is not very prominent in spectra of this type. It frequently shows by emission in $D_3$, and occasionally, even in the same star, by absorption at λ 4472; but its display is subordinate to that of other known and unknown elements.

The grand exemplar of the Wolf-Rayet class is γ Argûs (*alias* γ Velorum), a star of 2·4 magnitude, giving a resplendent spectrum ablaze with yellow and blue lines. It was first effectively studied by Professor Campbell in 1893-94,[1] although at the Lick Observatory the star barely attains an altitude of six degrees, and can be observed for only a few minutes on any one night. The main facts that struck him were the brilliancy

[1] *Astroph. Journ.* vol. ii. p. 177.

of C, the transitional character of F, and the unmitigated darkness of all the upper hydrogen lines. Similarly, the initial term of the Pickering series at λ 541 shows by emission, the rest by absorption, while a bright $D_3$ contrasts with a number of more refrangible dark associates. As usual, both blue bands are visible, but the weight of radiation falls upon that of shorter wave-length, the Rydberg line being comparatively inconspicuous. Miss Cannon found several of the hydrogen lines in both series to be dark with illuminated borders, an arrangement, as she remarked, the inverse of that prevailing in γ Cassiopeiæ and its allies.[1] Mr. McClean recognised oxygen absorption in this star,[2] and the feature is not unlikely to prove, on fuller inquiry, common to all the members of its class. The absence of H and K is more than probable, and suggests comparisons and reflections.

A 7·5 magnitude star in Cygnus (D.M. + 43° 3571) shows, like γ Argûs, a mixed succession of hydrogen lines, but modified, perhaps, by double reversals.[3] With the Lick thirty-six inch Professor Keeler perceived its spectrum as "an extremely complicated range of absorption bands and faint bright lines,"[4] the unusual width of which struck both him and Professor Campbell. Thus the azure bands actually overlap, forming a single indistinct glow one hundred tenth-metres broad. A spectrograph of this object, taken by Mr. Ellerman with the forty-inch Yerkes refractor, is described[5] as totally unlike any spectrum of the fourth type. Whether the dissimilarity is of a nature to be generalised so as to exclude all idea of kinship between these stellar families is more than we can tell at present.

A star of about the same brightness, distinguished as "Argelander-Oeltzen, 17,681," was swept up in Sagittarius by Pickering in 1881. In its spectrum the golden ray at λ 581 and the lazulite beam at λ 465 predominate almost exclusively. Vogel could see no others with the great Vienna refractor in 1883;[6] nevertheless, Campbell succeeded, ten

[1] *Harvard Annals*, vol. xxviii. p. 247.

[2] *Spectra of Southern Stars*, p. 15, Plate xii.

[3] Campbell, *Astr. and Astroph.* vol. xiii. p. 449; *Astroph. Journ.* vol. ii. p. 178.

[4] *Publ. Pac. Society*, vol. i. p. 81.

[5] Hale, *Yerkes Observ. Report*, ii. p. 6.

[6] *Potsdam Publ.* No. 14, p. 15.

years later, in measuring twenty bright lines in this wonderful spectrum.[1] Only one among them, and that of secondary importance, can be attributed to helium; but many due to that substance may be included in the unexplored absorption spectrum of "A.O. 17,681."

A star of 6·4 magnitude in Canis Major, catalogued as "Lalande 13,412," shows, instead of the unknown blue and yellow rays at λ 465 and λ 581, the "new" hydrogen lines at λ 469 and λ 541.[2] The spectrum includes, besides, a more refrangible blue band, centred about λ 461, but diffuse and divided. These multiple azure effulgences in the Wolf-Rayet stars offer a problem of singular interest. They possess none of the structure of genuine flutings; they seem apt to spread unsymmetrically. Is this an effect of pressure on the emitting vapour? Or does it arise from some property inherent in it, or some mode of action exerted upon it? The answers may be long postponed, but cannot fail to prove interesting.

A unique specimen of this class was photographically detected in Cygnus in the course of the "Draper Memorial" surveys.[3] It is extremely faint—below the ninth magnitude —and was enrolled in the Bonn Durchmusterung as D.M. +30° 3639. Nevertheless, its spectrum offers more than common facilities for exact observation, owing to the sharpness of its component rays. Thirty were measured by Campbell in 1893,[4] and they include, with many common to the type, several that appear to be individual to the star. The two brightest lines, however, are F and λ 569, the "citron" line strong in γ Argûs. The Pickering and Rydberg series are faint, while the alternative blue band at λ 465 glows intensely. But the distinctive feature of the star is that it is *spectroscopically nebulous.* Observed on the F-line like a solar prominence, Professor Campbell found it to present a very appreciable disc,[5] which, on narrowing the slit, became

[1] *Astr. and Astroph.* vol. xiii. pp. 460, 468.

[2] Campbell, *Astr. and Astroph.* vol. xiii. pp. 456, 468; Pickering, *Astr. Nach.* No. 3025; Vogel, *Potsdam Publ.* No. 14, p. 17; A. J. Cannon, *Harvard Annals*, vol. xxviii. pp. 147, 248.

[3] Pickering, *Astr. Nach.* No. 2986.

[4] *Astr. and Astroph.* vol. xiii. p. 461.

[5] *Ibid.* vols. xii. p. 913; xiii. p. 461.

reduced to a line, as shown in Figure 20. The length of this line is about 5″ of arc, and it measures the apparent diameter of the incandescent envelope of hydrogen which surrounds the body of the star. Only the hydrogen lines behave thus exceptionally; all the other spectral rays show as mere bright points upon the continuous background, which they do not transcend by a hair's-breadth. That is to say, hydrogen is the sole glowing constituent of the enormous appendage revealed by the powerful appliances available at the Lick Observatory. It has been seen nowhere else, but Runge[1] and Keeler[2] separately verified its existence.

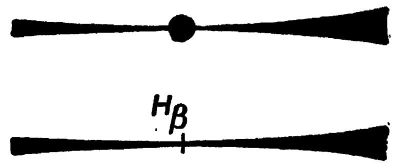



FIG. 20.—Hydrogen-Envelope of the Wolf-Rayet Star, D.M. + 30° 3639 (Campbell).

There are a few circumstances worth noting in connection with this extraordinary appearance. First, the vast spread of incandescent hydrogen round the star has no effect in thickening the representative lines of that substance in the star's spectrum. They are, on the contrary, particularly fine and narrow. The envelope, we can hence infer, is not an atmosphere; there is no appreciable downward pressure of its strata. Again, it must be—in the ordinary sense—hotter than the photosphere it surrounds; for the bright lines emanating from it are not reversed where they cross the prismatic thread due to the nucleus, as they should be if the nucleus were at a higher temperature than its envelope. Finally, it may be possible, by researches into the parallax and proper motion of this star, to form some estimate of its actual distance, and consequently of the real extent of its gaseous surroundings. Thus might be opened a novel line of inquiry destined to lead future students of the skies far afield.

The chemistry of the Wolf-Rayet stars—judging from partial interpretations of the disclosing script—is of the simplest. They have as unfailing constituents hydrogen and helium; oxygen is at least occasionally present, and the detection of nitrogen may be expected with some confidence. Sir William and

[1] *Astr. Nach.* No. 3471.
[2] *Astroph. Journ.* vol. viii. p. 113.

Lady Huggins showed in 1890[1] the inadmissibility of a carbon origin for any of the blue bands, and defined their positions by exact measurements. Professor Campbell's observations, visual and photographic, of thirty-two members of the class contributed materially to promote acquaintance with their peculiarities; yet they stimulated, rather than satisfied curiosity.

The distribution of these objects is strongly selective. They are virtually confined to the Milky Way. The rule is emphasised by its apparent exceptions, for the single specimen of the type deviating considerably in position from the galactic plane has proved, on closer inquiry, to be situated in a galactic offset; while the twenty-two grouped in the Magellanic Clouds belong to aggregations of the galactic order, and subject presumably to galactic conditions. The Milky Way, then, and the Nubeculæ afford analogous and exclusive facilities for the development of such bodies. They seem, moreover, to be provided more freely in some regions than in others, since the objects in question tend to collect into knots or groups, the finding of one Wolf-Rayet star being generally the prelude to additional detections in the same neighbourhood. Yet they rarely or never form binary combinations. They are loosely associated without any suggestion of mutual circulation. Nor has any of them, so far, given signs of spectroscopic duplicity. They are singularly steady light-givers. No Wolf-Rayet star is under the slightest suspicion of variability. Atmospheric incandescence on the largest scale is compatible in them with the perfectly uniform working of arrangements for the transference of heated matter from the interior to the surface of the radiating bodies. Considering the frequent and extreme instability of many bright-line stars of other varieties, this fact can hardly be too strenuously insisted upon.

[1] *Proc. Royal Society*, vol. xlix. p. 33.

# CHAPTER XI.

## THE GENERAL QUESTION OF BRIGHT LINES IN STELLAR SPECTRA.

THE more closely we study the phenomena of bright lines in stellar spectra, the more fully convinced we become that no single or simple principle avails to explain them. They are evidently produced under varied circumstances, at different elevations above the stellar photospheres, and in manifold forms of connection with the adjacent absorbent layers. Reviewing rapidly the chief types of emissive spectra, we can, to some extent, gather their implications.

The *sine quâ non* for the display of bright lines is the presence of a stratum in the star's atmosphere outshining the photosphere. The difficulty is indeed very great of attributing this superiority in brightness to a superiority in temperature; but it can be evaded by the use of Wiedemann's convenient term "luminescence," signifying a state of glow unconditioned in the strict sense by heat. The rationale of "luminescence" is still uncertain, but the introduction of the new idea it represents marks an important departure from the old groove of thought. Now we can trace two modes of emission in the sun, faintly indicated, it is true, but instructive as being within reach of comparatively immediate study. In the first place, some of the Fraunhofer lines seem to be relieved against vague effusions of light,[1] originating, almost certainly, beneath the reversing layer, among the interstices of the photospheric clouds. In the second place, the violet calcium lines, and occasionally one or two lines of hydrogen, are doubly reversed in the chromosphere. Both kinds of effect are reproduced in stellar spectra.

[1] Jewell, *Astroph. Journ.* vol. iii. p. 99.

Carbon stars show bright lines, which may be described as chromospheric; the gases emitting them surmount the vapours generating the noted dark bands. Moreover, these rays appear to be simple and uncompounded of bright and dark elements; they are not perceptibly affected by reversals or absorptions. The same may be said of the bright lines in Mira-variables. Yet the locality of their origin is widely different. They are essentially photospheric and deep-seated, shining from beneath the dusky flutings they diversify. The leading characteristic of bright-line helium stars is the duplication of their spectra. The vivid rays have dark companions. And this, not through the optical conjunction of two distinct bodies, but as the result of physical conditions prevailing in a single globe. In such stars, then, there are complex stratifications of emitting and reversing vapours diversely affected, we cannot tell how, by heat, pressure, magnetism, or electricity. The gradual penetration into the secrets of nature that must accompany their study offers an enticing, and a far from hopeless prospect to the rising generation of astrophysicists. But it will involve an indefinite expenditure of time and labour. The conditions of bright-line production in Wolf-Rayet stars are extremely hard to define. They probably vary greatly in individual specimens. The state of some probably resembles that of helium stars showing analogous symptoms of gaseous incandescence. The corresponding reversals, however, are less emphatic, and have indeed been rather suspected than perceived. Other members of the Wolf-Rayet class (for Campbell's star presumably has fellows) possess vast gaseous envelopes, uniformly glowing, and scarcely arresting light.

As to the theory of bright lines in stellar spectra, it is only certain that they testify to a real excess of incandescence in certain layers of the stellar atmospheres. They are not optically created by the concentration, through distance, of far-reaching, cool, gaseous appurtenances. This is proved by the example of the sun, by the study of Campbell's star in Cygnus, in which not a cool, but a strongly glowing appurtenance is actually visible, and by the phenomena of spectral variability, totally inexplicable on the view that mere extent of gaseous surroundings is competent to produce bright lines. It is

much easier, however, to deny than to affirm—to perceive incongruities with fact than to trace the lines of a true hypothesis. This cannot be done off-hand; much preliminary toil must be undertaken. Of prime necessity is the continuous study of the sun's facular rays, of their originating conditions, their displacements, their periodical changes. Laboratory inquiries will proceed simultaneously—inquiries into the nature of "luminescence," into the temperature of radiating gases, into the spectral effects of varied modes of electrical illumination, all which topics may demand subterfuges of treatment not yet easily imaginable. But need will stimulate invention, and knowledge will advance along the arduous ways by which alone future progress is possible.

# CHAPTER XII.

## ANOMALOUS AND VARIABLE SPECTRA.

A SMALL proportion of stellar spectra show marked individualities; they differ notably from the recognised types, and may help, by their very diversity, to elucidate them. Some belong to stars variable in light; most are probably inconstant in their peculiarities; none have as yet received the persistent attention that they deserve.

The "comet variable," R Geminorum, was last observed by Vogel in 1874,[1] and then not to the best advantage. A maximum, at which the star rose somewhat above the seventh magnitude, occurred 7th April, and during a month previously dark and bright bands were distinguishable in its spectrum. Repeated measurements proved the latter to coincide in position with the dusky colonnade in fourth-type stars. They were due, quite unmistakably, to the direct radiations of carbon. The variable, in other words, glowed with a light fundamentally the same in quality as that of a comet approaching perihelion. No hydrogen or helium lines seem to have been present; but the strong yellow ray located at λ 581 must be identified with the Wolf-Rayet line,[2] specially associated, as we have seen, with the lazulite band at λ 465. It will be interesting to learn whether the same connection subsists in the variable; but some years must elapse before any kind of new information regarding it can be obtained. Just at present the star, in its bright phases, is too near the sun for purposes of useful research, and its period of 370 days differs so little from a year that the conjunction passes off with extreme slowness. The minima of this curious variable carry it to the very

[1] *Astr. Nach.* No. 2000. [2] Frost-Scheiner, *Astr. Spectroscopy*, p. 323.

verge of extinction, below the range of ordinary telescopes. The attempt has not yet been made to keep it in view with those of large aperture.

A star capriciously variable both in the kind and in the quantity of its light was discovered by Pigott in 1795. Usually almost constant at the sixth magnitude, R Coronæ is liable, at intervals counted by years, to lapses into obscurity,[1] varied by spasmodic efforts towards recovery, each crisis of instability lasting many months. The spectral fluctuations of the star seem unrelated to its changes of brightness. They were first noticed by Mr. Espin in 1890, but so far have not been very clearly defined. Migrations from type to type are somewhat vaguely indicated; their reality would involve so much that is novel and surprising that it can only be admitted on irrefragable evidence. On 14th September 1890[2] the spectrum appeared of Type iv.; it was interrupted by obscure bands held to be those of carbon absorption. In April 1893[3] bright lines and nondescript dark bands alternately stood out to view and became effaced; and on 4th May 1899[4] a spectrum resembling that of the sun had established itself. Mr. Espin is convinced that a double light-source is in question, and that the observed changes are explicable by the conjunctions and elongations of revolving stars, giving contrasted spectra; but unless they can be brought into conformity with some time-regimen, such an hypothesis is evidently inapplicable.

The spectrum of a star in the Shield of Sobieski is probably analogous to that of R Coronæ, but the suspected variation is not from the fourth, but from the third to the second type. In August 1890 Mr. Espin derived from R Scuti a set of faint bands, modelled to all appearance on those of Mira or *α* Herculis;[5] a glimmer of bright lines in the blue and violet, however, betrayed unusual characteristics, completely drowned, like the concomitant absorption, in the flood of continuous light accompanying and occasioning the maximum in October. Less than two years later, 25th

[1] Argelander, *Astr. Nach.* No. 624.

[2] *Monthly Notices*, vol. li. p. 12; Krüger, *Cat. der färbig. Sterne*, p. 81.

[3] *Astr. Nach.* No. 3200.

[4] *Ibid.* No. 3633.

[5] *Monthly Notices*, vol. li. p. 12.

June 1892, Dr. Krüger found the spectrum definitely solar, the *b*-group of magnesium being particularly distinct.[1] R Scuti never sinks below the ninth magnitude. It is then at all times fairly accessible to exact investigations, which should serve, without much difficulty, to fix the true nature of this still enigmatical object. The mode of spectral variability which it exemplifies is not generally accounted as possible by those who undertake to discuss the intricate subject of stellar development; this could hardly, indeed, be dealt with on the old lines if the suspected phenomenon proved to be an unquestionable fact.

Spectral and luminous variability are, in certain stars, inseparably connected. With increasing light the hydrogen lines brighten; with ebbing light they fade. A common cause evidently governs the two kinds of change. This close correspondence is observed only in periodical objects of the Mira-class. Variables of a less regular type, such as R Coronæ, fluctuate spectrally in apparent disregard of their light-vicissitudes; while yet a third description of spectroscopic variables are exempt from the least suspicion of instability in brightness. A conspicuous example of the last kind is $\gamma$ Cassiopeiæ.

Normally, the red hydrogen line is the brightest in its spectrum; yet it seemed extinct when looked for by Dr. Vogel, 18th June 1872.[2] To the Dunecht observers, however, it showed "superbly" bright 20th December 1879,[3] then lapsed into invisibility, until rekindled under the eyes of Von Gothard at Herény, 13th August 1883.[4] Since then it has not been missed, but has rarely been sought; for it can scarcely be called accessible to spectrographic observation, and direct inspection of stellar spectra has unfortunately fallen out of vogue. On 13th September 1885 Dr. Copeland found C very bright in $\gamma$ Cassiopeiæ, F just measurable;[5] on fifty-two plates taken at Stonyhurst during the years 1891-99[6] F was "superlatively bright," C being of course below their range. No evidence was elicited from them of alteration

[1] *Cat. der färbig. Sterne*, p. 99.
[2] *Bothkamp Beob.* Heft ii. p. 146.
[3] Copeland, *Monthly Notices*, vol. xlvii. p. 92.
[4] *Astr. Nach.* No. 2539.
[5] *Proc. Royal Society*, vol. lvii. p. 174.
[6] *Monthly Notices*, vol. lix. p. 505.

in the hydrogen spectrum, but they gave strong grounds for suspicion of change in lines due to other substances, notably in a strong ray at λ 4586, doubtfully associated with vanadium. Suspicion might have been raised to certainty if the yellow helium line had fallen within the scope of inquiry, for the variability of $D_3$ in this star may safely be taken as proved. Although observed as bright by Secchi in 1867,[1] measured by Von Gothard 20th August 1883,[2] and just recognised at the O Gyalla Observatory in 1891, and at South Kensington late in 1889 and 1894,[3] the line is commonly invisible under the most favourable conditions. Keeler could not find it with the great Lick refractor in the summer of 1889;[4] three spectrograms, taken on orthochromatic plates with the Pulkowa thirty-inch by Bélopolsky in 1892, bore no trace of it;[5] its emergences, in brief, are so transient and uncertain as to be altogether exceptional. They seem quite casual—that is to say, their law of causation is to us inscrutable. The remaining chief lines of helium in γ Cassiopeiæ are dark, with indications of fine bright reversals at their centres.[6]

The metallic spectrum, too, is unmistakably variable. Von Konkoly noted sodium absorption at D, 15th September 1884.[7] Yet Keeler's examination, five years later, showed the spectrum in that vicinity to be absolutely continuous. No subsequent record of dark D has probably been made. The magnesium group *b*, on the other hand, seen dark by Keeler, appeared bright on the Stonyhurst photographs, and it was accompanied by the blue emission from "high temperature" magnesium at λ 4482. No iron lines are brightened in this spectrum. A clue to its intricacies may be found by the employment of combined visual and photographic methods. Neither by itself is altogether satisfactory. Changes in one part of the spectrum lose half their significance unless correlated with changes in the remaining parts. The assurance of their reality, besides, would be immensely strengthened by the demonstration of their not being isolated. Sympathetic

[1] *Sugli Spettri Prismatici delle Stelle*, Mem. ii. 1868.

[2] Frost-Scheiner, *Astr. Spectroscopy*, p. 256.

[3] Lockyer, *Proc. Royal Society*, vol. lvii. p. 173.

[4] *Publ. Pacific Society*, vol. i. p. 80.

[5] *Astr. Nach.* No. 3129.

[6] A. C. Maury, *Harvard Annals*, vol. xxviii. pp. 124, 126.

[7] *O Gyalla Beob.* Bd. vii. p. 14.

variations, independently recorded, could hardly be the creation of instrumental or other extraneous causes.

The chromospheric instability of $\gamma$ Cassiopeiæ is shared by a good many other stars. Among them is J Velorum (A.G.C. 14,145), spectrographically registered at various dates in the course of the Harvard College southern surveys of the heavens. Miss A. J. Cannon's examination [1] showed that on the plate taken 2nd June 1893 the green and blue hydrogen lines ($H\beta$ and $H\gamma$) were bright, superposed upon broad absorption bands. Nevertheless on 19th April 1895 and 19th March 1896 they were simply dark, with no trace of vivid reversals. And so they remained in 1899. Whether the red line, usually in such stars the most brilliant of the series, responded to the chromospheric extinction attested by its more refrangible associates, can never now be known; but something may, in the future, be discovered about its behaviour should the spectrum of J Velorum ever be rekindled. The star, which is of the fifth magnitude, does not vary appreciably in lustre.

An inverse change to that observed in J Velorum was detected by similar means in a seventh-magnitude star in the southern constellation Chamæleon (A.G.C. 14,686). On 20th May 1892 it appeared to be of the Sirian type; hydrogen showed only by absorption; but on 3rd April 1895 $H\beta$ was bright, eighteen days later $H\gamma$ had followed suit, and fringes of light seemed attached to the lower edges of two of the ultra-violet hydrogen lines.[2] The progressive incandescence, betokened by the creeping upward of the illumination, was a complete novelty; its probable initial symptom in the blaze of C necessarily remained unnoticed. It is earnestly to be hoped that this unique object may not slip out of view amid so many conflicting claims for attention advanced by the denizens of the southern heavens.

A star in Canis Major (A.G.C. 9181) [3] is distinguished by frequent fluctuations from brilliancy to obscurity of the green and blue hydrogen lines. Miss Cannon has traced their spectrographic history since 1892. The more refrangible members of

[1] *Harvard College Circular*, No. 32; *Annals*, vol. xxviii. p. 183.
[2] *Harvard Circular*, No. 32.
[3] *Ibid.* No. 21; *Annals*, vol. xxviii. p. 184.

the series are present—it can be inferred—as absorption lines, and C is explicitly stated by Campbell to have been glowing in 1894.[1] Variations of its green companion (H$\beta$), analogous to those just described, have recently been detected in the spectra of $\eta$ Centauri and $\kappa^2$ Apodis.[2]

The percentage of abnormal stars found on the Draper Memorial plates is exceedingly small; yet they sum up to a not insignificant total. A few may be named as worthy of sustained attention. A sixth-magnitude star in Libra (A.G.C. 20,937) was announced in 1895[3] to show a spectrum resembling that of the great Looped Nebula (30 Doradûs), which differs in light-quality from other gaseous nebulæ; and a stellar apparition in the Centaur, then visible, was added to the spectral group. "Nova Centauri" promptly disappeared, but the star in Libra is permanently present, and available year by year for prismatic comparisons. The peculiarities of the following objects have not been expressly defined:—

1. S.B.D.—22° 1070; R.A. $5^h$ $14{\cdot}5^m$; Dec.—22° 19′. Mag. 8·7. Photographed at Arequipa.[4]

2. Z.C. $17^h$ 734; R.A. $17^h$ $13{\cdot}2^m$; Dec.—66° 15′. Mag. 8·5. Photographed at Arequipa.

3. S.D.M.—8° 1467; R.A. $6^h$ $28{\cdot}1^m$; Dec.—8° 48′. Mag. 8·5, but slightly variable.[5]

4. S.D.M.—11° 1941; R.A. $7^h$ $22{\cdot}4^m$; Dec.—11° 31′. Mag. 8·9 variable. Banded spectrum of uncertain type.

5. S.D.M.—10° 5057; R.A. $19^h$ $7{\cdot}7^m$; Dec.—10° 54′. Mag. 7. Unique spectrum of bands.[6]

Possibly the original records secured of these stars may never be duplicated, since they are not unlikely to be spectrally variable as well as peculiar. In any case their characteristics, which are precisely of the kind to prove specially instructive, need to be more fully ascertained.

The spectra of $\phi$ and $\psi$ Persei—both bright-line helium stars—have been suspected of fluctuations; but those of the

[1] *Astroph. Journ.* vol. ii. p. 180.

[2] *Fifty-fifth Harvard Report*, p. 10; *Harvard Circular*, No. 60; *Annals*, vol. xxviii. pp. 180, 183.

[3] Fleming, *Monthly Notices*, vol. liii. p. 275; *Harvard Circular*, No. 4.

[4] *Astroph. Journ.* vol. i. p. 411.

[5] *Harvard Circular*, No. 32.

[6] Fleming, *Astr. Nach.* No. 3054; *Astr. and Astrophysics*, vol. xi. p. 27.

first may depend upon varying radial velocity,[1] while those of the second, although slight in amount, are of a particularly interesting description. They consist in the occasional shifting of the brilliant narrow F of hydrogen to one or other side of the absorption-band upon which, in general, it is centrally placed.[2] These displacements are probably of the same nature as the alternate marginal illuminations of H$\beta$ in $\theta$ Orionis and 11 Monocerotis; they are certainly unconnected with revolving movements in a system of bodies. Many more instances might be given of stellar spectra apparently abnormal, and at least ostensibly variable, but the above may suffice as specimens.

[1] *Astroph. Journ.* vols. x. p. 365; xvi. p. 114.

[2] A. C. Maury, *Harvard Annals*, vol. xxviii. p. 104.

# CHAPTER XIII.

## COLOUR VARIABILITY.

COLOUR variation in stars is a somewhat elusive phenomenon. It cannot be measured; no "colorimeter" yet constructed has given satisfactory results. Then it is subject to adventitious modifications depending upon the state of the atmosphere, the fluctuating sensitiveness of the retina, the nature and aperture of the telescope employed. The same observer after a prolonged vigil will often receive quite different chromatic impressions from those derived with unfatigued sight; nay, his right and left eyes may sometimes pronounce incongruous judgments upon a colour-harmony or a colour-contrast. Such counterfeit changes, however, are slight and evanescent; with due care they can always be separated from intrinsic variations. The endless individualities of colour-vision have, indeed, also to be taken into account. There is no branch in which personal equation tells so heavily, yet so intangibly. Hence casual anomalies of description hardly raise a presumption of actual change. Evidence that it has occurred can only be admitted with extreme caution. The difficulty is to disengage what really deserves consideration from the multitude of floating statements tending only to bewilderment.

Three kinds of colour-variation may be discriminated. They severally affect periodical stars, red stars fairly constant in light, and tinted star couples.

(1) Stars with a light-cycle of less than a hundred days are usually of an unchanging yellowish hue; but "long-period" variables are characteristically red, and redness in stars appears to be rarely a fixed or stable property. It might be compared to an external covering capable of alteration in opacity, or even of entire removal, and connected in

its effective action with complex, more or less unsettled conditions. Very commonly, the rises and descents in magnitude of such stars are associated with fadings and flushings of colour, a deeper tint generally accompanying a low light-phase. For this there is a double cause, in the diminution of brightness, and in the increase of absorption. The first acts physiologically. A faint ray strikes the eye as redder than one more brilliant, although both be of the same refrangibility. The second works objectively. Absorption in stellar atmospheres tells mainly on the blue end of the spectrum. Hence, as darkening closes in upon the shorter wave-lengths, the stars redden more and more. Mira, which is not properly a colour-variable, shows this effect markedly. Certain objects of the same class, however, change more radically, and less consistently. Their fluctuations in hue correspond very partially to their fluctuations in light. Colour-change seems to progress independently, and from a superficial point of view quite capriciously.

At Sir Cuthbert Peek's observatory near Lyme Regis, a score of variable stars have been kept under watch since 1887. The data regarding them collected by Mr. Grover are remarkable and suggestive in several particulars, especially as regards the correlation of colour with magnitude. An important example is afforded by S Herculis, a star varying from the seventh to the thirteenth magnitude in about ten months. It is strongly red with a fine fluted spectrum, yet has, at sundry times, been seen completely blanched. We extract from the *Rousdon Observations* some notes of its colour, with the corresponding dates and magnitudes.

*S Herculis*

| Date. | Magnitude. | Remarks. |
|---|---|---|
| 1886, Nov. 12 | 9·4 | White, sharp, and distinct. |
| ,, Nov. 29 | 8·5 | Decided red. |
| 1887, May 16 | 10·9 | White; little, if any, colour. |
| ,, Dec. 20 | 7·3 | Deep ruddy. |
| 1888, Oct. 15 | 6·5 | Fiery red. |
| 1889, June 29 | 9·0 | Dull greyish. |
| ,, Sept. 30 | 8·3 | Deep coppery red. |
| ,, Oct. 22 | 9·1 | Blood red, well defined. |
| 1890, May 23 | 9·1 | Grey or ashen colour. |
| 1891, May 12 | 6·8 | Brilliant scarlet. |
| 1893, Aug. 17 | 9·3 | Dull white, well defined. |
| 1894, Sept. 8 | 7·5 | Nearly white, sharp. |

No trace of regularity is perceptible in these changes. The mean magnitude of the star when white was 9·0, when at its reddest, 8·5. They are then obviously unrelated to its light-phases.

An analogous object is T Ursæ Majoris, which alternates between deep red and "creamy," or pure white, though with a decided tendency to assume paler tints as brightness increases. A typical pair of observations were made on 5th and 14th February 1893. On the first evening T Ursæ was estimated as of 10·1 magnitude, and of a "deep, dull, ruddy hue"; on the second, it had risen to 9·3 magnitude, and become a "dull leaden colour," showing "no trace of orange or red—a very curious change," and one altogether unaccountable. Spectroscopic information, simultaneously procured, would have been likely to prove instructive, but none, unfortunately, is available.

A counter-example to T Ursæ is S Cephei, which, observed under the same conditions, and undergoing similar variations of brightness, was nevertheless recorded as at all times conspicuously red. On the other hand, $\chi$ Cygni, a flagrantly red variable of the Mira type, occasionally divests itself of colour as it brightens, although "scarlet" maxima are more common than "white." Espin's observations confirm the striking variability in hue of $\chi$ Cygni. On the whole, it cannot be doubted that temporary whiteness is a frequent feature of this class of ruddy stars, and the fact implies a great deal.

(2) In the second class of colour variables, light-change supervenes incidentally or not at all. It includes two historic examples—Sirius and Algol, both exceedingly unlikely, yet both attested on good authority to have been red within the scientific memory of man. The Sirian question has been exhaustively discussed by Dr. See [1] and by M. Schiaparelli; [2] their arguments are of most curious interest, but we can here only attempt to give what appears, on a fair view, to be their upshot. Two facts are incontestable; Seneca compared the colours of Mars and Sirius, and pronounced the star to be more intensely red than the planet, and Ptolemy applied to

[1] *Astr. and Astrophysics*, vol. xi. pp. 269, 372, 550.

[2] *Atti dell' Accad. degli Agiati*, t. ii. 1896.

it his current epithet for "glowing ruddy" objects (ὑπόκιρρος), a piece of evidence vainly sought to be explained away as a transcriber's error. Many other ancient authors imply, or are held to imply, what Seneca and Ptolemy definitely state; but even apart from these confirmatory hints, the simplest and perhaps the safest course appears to be to accept such definite statements. Their improbability does not in itself warrant their rejection. It has been suggested that the rapid scintillation of the Dog-star may have lent to it a fictitious redness, but it does not do so now. "Sirius is glancing blue-bright like a spirit," Carlyle wrote from Templands in April 1842. And certainly the atmospheric disguise of colour cannot have been less effective in Dumfriesshire than at Rome or Alexandria. In the *Iliad*, a fiery nature and aspect are ascribed to Sirius; but Homeric indications are often loose or figurative. They, however, lend in this case countenance to the plausible surmise that the redness of the star was of antique standing. As to the date of its vanishing, nothing positive can be asserted; but the negative testimony of Al-Sûfi places it almost conclusively before the tenth century.

The same Persian astronomer supplies the only extant notice of Algol's early redness. Perhaps a merely temporary phase, it seems nevertheless to have recurred after nine centuries. This was in 1841, when Schmidt at Athens perceived the star as yellowish red,[1] although its subsequent whiteness was patent to him as to all other observers. Was Schmidt deluded? It is very difficult to determine. Only the star itself can authenticate, by renewing, its evanescent glows of colour.

The pronounced redness of a seventh-magnitude star, No. 8 in Schjellerup's "Red" Catalogue,[2] was recorded by Oeltzen during his revision of Argelander's northern zones. Copeland, nevertheless, found it white, 1st January 1876; Espin, yellow, with a continuous spectrum, 14th November 1887; while Krüger registered on 6th October 1891 well-developed bands of the third type corresponding to an orange tint. Again, a ninth-magnitude star in Taurus[3] appeared to Hind

[1] *Astr. Nach.* No. 1099. [2] Krüger, *Cat. der färbig. Sterne*, p. 9.
[3] Known as "64 *b* Schjellerup" = Krüger 513. See *Cat. der färbig. Sterne*, p. 33.

"very red," 3rd September 1848, but "bluish" 14th November 1850. Lost sight of for a quarter of a century, it was next observed by Copeland in January and February 1876 as pale yellow, and by Doberck, three years later, as reddish orange. Finally, on 10th January 1888, Espin saw it white, with a seemingly continuous spectrum; since when no attention—that the present writer is aware of—has been paid to it. A much brighter star in Aquila[1] (seventh magnitude) showed red to Schjellerup in 1863, but to Birmingham colourless in 1872 and 1874, and *blue* 18th May and 20th July 1873. These changes were in a manner verified by subsequent spectroscopic observations; for the object, which had then recovered a ruddy tinge, was classed by Espin as of the fluted type, 20th September 1889, but by Krüger, 25th June 1892, as a solar star with a pale yellow cast. The colour-phases of an eighth-magnitude star, "63 Schjellerup,"[2] are attested by the best authorities; it is impossible to doubt their reality. Picked out for its redness at Copenhagen in 1863, the object, after numerous alternations, was described by Franks in 1885 as white. No later observations appear to be extant.

The following short list of the best-authenticated colour-variables may be useful to observers:—

[1] No. 6803 of the *Copenhagen Catalogue* = 214 Schjellerup = Krüger 1436.
[2] Krüger 504.

[TABLE.

| Designation. | Magnitude. | Remarks. |
|---|---|---|
| 5 Schjellerup =Krüger 75 | 7·0 variable ? | "Full garnet," J. Herschel; red, Schjellerup, 1863; white, Dreyer, 1876. |
| 8 Schjellerup =Krüger 102 | 7·0 | Deep red about 1850; white, 1st January 1876. |
| 63 Schjellerup =Krüger 504 | 7·8 | Rubra, Schjellerup, 1863; blue, Birmingham frequently in 1873; decided red, Gould; colourless, Dreyer, 1880. |
| 90 Schjellerup =Krüger 687 | 7·7 | Rubra, Struve; bluish white, Birmingham, 1874; orange, Dreyer, 1879; white, Espin, 1888. |
| 93 Schjellerup =Krüger 698 | 9·0 | Blood red, Schjellerup, 1863; orange, Copeland, February 1876; colourless, Espin, 10th February 1888. |
| $\gamma$ Circini[1] | 3·4-5·2 | Very red, Gould, about 1875; white, Stanley Williams, 1886. |
| 64 *b* Schjellerup =Krüger 513 | 8·8 | Very red, Hind, 1848; bluish white, Hind, 1850; red, Dreyer, 1879; white, Espin, 1888. |
| 148 Schjellerup =Krüger 983 | 8·5-9·5 | Scarlet, Rosse, 1861; dark red, d'Arrest, 1866; colourless, Birmingham, 1874; red, intense bands, Dunér, 1878. |
| 214 Schjellerup =Krüger 1436 | 7·0 | Red, Schjellerup, 1863; not red, Birmingham, 1872, 1874; blue, Birmingham, 1873; orange, fluted spectrum, Espin, 1889; yellowish, solar spectrum, Krüger, 1892. |
| *r* Velorum | 5·0 | Red, Gould, 1870-73; leaden white, 1888, A. M. Clerke; slight red tinge, Tebbutt, 1891. |
| 222 *b* Schjellerup =Krüger 1512 | 7·8 | Red, Lamont; yellow, Dreyer, 21st July 1875; white, Dreyer, 18th August 1875; yellow, Espin, 1889; white, Krüger, 1891. |

Two stars[2] have been mentioned in an earlier chapter as anomalously white, considering that their spectra are of the fourth type. The possibility should not be overlooked that their paleness is only temporary. They are perhaps colour-variables, and will, at some future time, show the ruddy hue appropriate to the quality of their light.

(3) The colour changes of double stars are a peculiarly baffling subject of inquiry. Many have been recorded that can safely be dismissed as illusory; some that are unquestionably real. Yet in most cases there is a large element of doubt. Personal idiosyncrasies come strongly into play; meteorological influences, instrumental diversities, and all the

[1] Binary in slow motion (Innes). Composite spectrum (A. J. Cannon).

[2] S.D.M. – 10° 513 and S.D.M. – 10° 5057 of eighth and seventh magnitudes respectively.

chances and changes of existence swell the reckoning of uncertainty. To say nothing of the indeterminateness of language. Star tints are often so delicate as to defy verbal definition. Distinctions between rose-pink and amethyst, sea-green and apple-green, ashen, lilac, and grey, have only a nominal meaning. These tender shades, moreover, while escaping some eyes altogether, are enhanced by others into vivid contrasts; and hence observers, expecting to see star-couples glowing like fruits of the Hesperides, are apt to carry away the impression that the subtle coloration actually presented to them implies a marked change. To separate the kernel of fact from the husk of opinion or illusion is then no easy matter. Yet an inadequate attempt to banish confusion is almost always better than none, and may here be worth making.

The more closely the chromatics of double stars are studied, the more clearly emerges an irreducible minimum of change. A satisfactory example is afforded by one of the most carefully watched binaries in the heavens. The primary in 70 Ophiuchi is of 4·5, the satellite of 6·5 magnitude, and it is unquestionably the satellite which conspicuously varies in hue. Sir William Herschel in 1779 perceived in it a very slight reddish suffusion, and J. Herschel and South described the pair in 1824 as "white and livid." Yet the elder Struve, an incomparable authority, considered their "yellow and purple" tints remarkable enough to warrant their inclusion in a restricted list of objects showing *colores insignes*,[1] and they were still "topaz and violet" when observed successively by Smyth and Webb.[2] "Gold and purple" again they appeared in July 1883 to Perrotin at Nice, although less than a month previously he had noted them "greenish yellow and reddish yellow," while a year later he recorded them as "golden and orange."[3] This vesture they continue to wear. They are ordinary yellowish stars with an ordinary solar spectrum. Sooner or later, however, the companion may be expected to put off its crocus-veil and shine Tyrian-hued.

The stars of $\gamma$ Delphini are now finely contrasted in orange and green. They appeared, nevertheless, white to the elder

[1] *Mensuræ Micrometricæ*, p. lxxxi.
[2] *Intellectual Observer*, vol. ii. p. 138, 1863.
[3] *Annales de l'Observatoire de Nice*, t. ii.

Herschel in 1779; white and yellowish to Herschel and South in 1824; "reddish yellow and greyish lilac" to Gore in 1874;[1] pale rose and light green to Dembowski in 1876-77; orange and green to Flammarion in 1877. Moreover, the companion showed "light emerald" during the years 1831-39, but "flushed grey" in 1850. Doberck found it bluish in 1882, and the primary yellow;[2] Vogel in 1883 recorded both stars as creamy white; while in 1895—according to Mr. Franks—the colours were "very pronounced, the chief star being a strong yellow and the companion greenish."[3] They are of fourth and fifth magnitudes respectively, and a sky-gap of 11″ divides them. Their mutual revolutions have made little sensible progress during a century and a quarter, but their common drift through space certifies their systematic connection.

The case of 95 Herculis is somewhat perplexing.[4] This is an equal pair of fifth-magnitude stars, rigidly fixed during the last twelve decades at an apparent distance of 6″. Their "magnificent tints of orange and green" excited Father Secchi's admiration in 1855; and Piazzi Smyth was accustomed to see them "apple green and cherry red" until 29th July 1856, when he perceived with stupefaction, from his point of vantage on the Peak of Teneriffe, that both were of the undistinguished white attributed to them by Herschel in 1780. Fitful and partial displays of their original chromatic brilliancy appear to be vouched for by Dunér's and Flammarion's[5] observations of the stars as "bright green and yellow," and "gold and azure"; but their pale primrose is now unrelieved by a shade of difference. There is no good reason to doubt that, in the earlier part of the century, they were marked by vivid complementary colours. Obvious to Webb, they were remarked by Admiral Smyth as an unusual instance of diversity in tint "between components so nearly equal in brightness."

Instances are not infrequent of the small star in pairs of disparate brightness varying in colour; but the relation is

[1] Webb, *Celestial Objects*, 4th ed., p. 297; *Knowledge*, vol. xiii. p. 250.

[2] *Astr. Nach.* No. 3023.

[3] *Journ. Brit. Astr. Ass.* vol. v. p. 457.

[4] *System of the Stars*, p. 159.

[5] *Les Étoiles*, p. 690.

never inverted; no primary is exclusively subject to change of tint. The satellite of δ Herculis, a greenish star of the fourth magnitude, appeared to Struve alternately grape red and ashen white; to Dembowski, blue; to Knott, bluish green in 1850, ruddy purple in 1871; to Fletcher, in 1851, red; to Flammarion, violet. The conjunction of these stars is thought to be merely fortuitous. They are moving along divergent straight lines, and hence seem destined to definitive separation. Yet colour-changes of the kind affecting the satellite do not occur in isolated objects, and would rather imply a physical connection with a dominating orb. It will then be of particular interest to determine quite certainly whether δ Herculis is a truly gravitational, or simply an optical couple.

The companion of δ Cygni shows analogous variations. "Ashen grey" to Struve's perception during the years 1826-33, it surprised him with a strong red glow in 1836; three years later, Dawes found it blue; Secchi, by turns red, blue, and violet in 1856-57; Dembowski, grey in 1862-63; Engelmann, red in 1865. Of late its blue aspect has predominated; yet Perrotin recorded it as yellow or orange with the great Nice refractor both in 1883 and in 1886. These stars make a very much closer pair than δ Herculis, and are in slow orbital movement.

Two at least of the four stars grouped in σ Orionis may be admitted to fluctuate in hue.[1] One of 7·5 magnitude appeared ashen grey in 1837, ruddy in 1851 and 1869, bluish in 1883. A more distant, somewhat brighter component, usually dust-coloured, was marked "grape red" by Smyth in 1832. Even the chief star is not of the perennial whiteness that should match its helium spectrum. Webb found it yellow in 1851, and Gould entered it as "red" in the Argentine Uranometry. It was divided by Burnham in 1888 into an excessively close pair (fourth and sixth magnitudes at 0·26″), which, already in 1891, gave indications of circulatory movement.[2]

The following is an enumeration of some double stars reputed, on good grounds, to be colour-variables:—

[1] Webb, *Cel. Objects*, vol. ii. p. 182.
[2] Burnham, *Astr. Nach.* Nos. 2875, 3114.

| Designation. | Magnitudes. | Distance. | Remarks. |
|---|---|---|---|
| 70 Ophiuchi =Σ 2272 | 4·5, 6·5 | 1·6″ | Primary white or yellow, satellite alternately purple, rosy, and yellow. Spectrum, solar. |
| γ Delphini =Σ 2727 | 4, 5 | 11″ | Primary cowslip to orange; companion emerald to blue, lilac, and topaz. Spectra, solar and Sirian. |
| 95 Herculis =Σ 2264 | 5·3, 5·3 | 6″ | Contrasted green and red to uniform yellow. Spectra, solar and Sirian. |
| δ Herculis =Σ 3127 | 4·0, 8·5 | 26″ | Companion by turns ashen, red, violet. Chief star gives a helium spectrum. |
| δ Cygni =Σ 2579 | 3, 8 | 1·5″ | Satellite grey to red, blue, or green. Slow binary. Large star gives a Sirian spectrum. |
| σ Orionis =Σ 762 | 4·1, 7·5, 7·0 | 13″, 41″ | Chief star white to reddish; helium spectrum. Companions grey to ruddy. Fixed. |
| 38 Geminorum =Σ 982 | 5·5, 8·0 | 6·8″ | Companion varies in magnitude, 7·5 to 10; in colour, from bluish (1829) to red (1856, 1863), and azure (1872). |
| γ Leporis | 4·0, 6·5 | 93″ | Companion pale green, 1832; garnet, 1851 and 1874 (Webb). Chief star gives a solar spectrum. |
| γ Serpentis | 4·5, 9·0 | 51″ | Small star lilac, 1832; "native copper," 1851 (Webb). |

Colour-variability has hitherto been only observed, as it were, in passing. And the casual study of a subject is seldom effectual. Here much more is required if any progress is to be made towards discovering the laws and cause of the phenomenon. What is essential to ascertain is the nature of the spectroscopic response to colour-change. On this side the problem can be attacked with some hope of getting nearer to a solution. If visual alterations of hue can satisfactorily be brought to the test of prismatic analysis, the way will be thrown open for an important gain of knowledge; while it is hard to see by what other means ignorance on the curious topic we have been discussing can be dissipated. It is not, indeed, always easy to combine work in different branches; yet the correlation of results is a vital need of astronomy, and scarcely ever fails to prove especially and widely illuminative.

# CHAPTER XIV.

## THE SPECTRA OF DOUBLE STARS.

THE spectra of double stars stand in the closest relations to their colours. This, indeed, is almost a truism, since spectra merely show in detail what is summarised in mixed tints. Yet the two forms of statement are not tautological. The result of prismatic analysis cannot be wholly anticipated from the visual impression. The eye makes no attempt to reduce its sensations to their elements. Totally different rays may be blended and balanced so as to produce an identical sum-total to the perception of the optic nerve. Nor would it be in all cases easy to pronounce upon the colour of a star from the simple inspection of its spectrum. One cannot tell beforehand, so to speak, how the eye will take things. Some scarcely measurable reinforcement of selective stoppage, a few rays of absorption added or removed, may make the difference between rosy and golden, or purple and pink. Thus neither direct nor prismatic observations are superfluous; but the latter, as affording scientifically accurate and—through photographic means—permanent records, are by far the more important.

The spectra of double stars unlike in colour are usually of different types; and here a remarkable rule applies. Contrasted pairs are, with few and doubtful exceptions, notably unequal in brightness, and the warmer tint invariably belongs to the larger component. Blue, green, or violet stars are always the satellites of red or yellow primaries; and, in accordance with these indications, they give first-type spectra, while their brighter and more ruddy neighbours show Antarian flutings or solar lines. We are thus led to the unexpected

conclusion that, of two globes simultaneously contracting, the larger, which should naturally cool more gradually, and therefore run through its evolutionary stages at a more leisurely pace, attains solar standing while its companion still remains a "white star." This relation is the very crux of cosmic growth-theories; something more will be said about it in the next chapter.

The separate spectral examination of coupled stars is far from easy, and has indeed rarely been attempted. Only by Sir William and Lady Huggins has the subject been prosecuted systematically and with success. Their application to it of photography, rendered possible by the completion, in 1897, of an ingeniously devised reflecting slit, constituted in itself an immense advance. Previously, only the superposed spectra of double stars had been chemically recorded, and these, for discriminatory purposes, were of no more than provisional use. One coloured pair, however, presents less difficulty in this respect than the rest. The components of $\beta$ Cygni lie far enough apart to give distinct spectrographic images, formed by an objective prism, on the Draper Memorial plates.[1] Specially inviting as well to direct scrutiny, they were among the earliest objects subjected to Sir William Huggins's light-analysis.

The pair consists of a third-magnitude "topaz" star and a fifth-magnitude "sapphire" at 34″. The unaltered value of this interval since Bradley's measurement of it in 1755 almost assures us that they drift together through space under the stress of a physical bond. For their proper motion, though very small, would have sufficed, in the course of a century and a half, to produce unmistakable relative displacement. Blue stars, besides, are never solitary; and the companionship upon which their uncommon hue depends must evidently be real, not simply optical. Plate IX. Fig. iv. shows the spectra of these stars as photographed by Sir William and Lady Huggins.

Their complete diversity is apparent at a glance.[2] The hydrogen series is writ large and strong on that of the minor luminary; helium absorption is not apparent; the Sirian type

[1] A. C. Maury, *Harvard Annals*, vol. xxviii. pp. 93, 99.
[2] *The Observatory*, vol. xxii. p. 387.

is pronounced. Of solar quality, no less decidedly, is the golden light of the primary. Yet it cannot escape notice that the photographed spectra do not explain the vivid colouring of $\beta$ Cygni; they might have been taken (speaking broadly) from any two stars of the types represented. This, indeed, was just what should have been expected, since the special absorption differentiating them from the common run of stars was known to lie outside the range of sensitiveness of ordinary plates. As regards the blue member of the pair, at any rate, there could be no doubt of the fact. A set of dark bands, cutting out a goodly proportion of its yellow and orange rays, were observed by Sir William Huggins in 1864,[1] and again by Dr. Vogel in 1872,[2] and they correspond with, and fully explain, its chromatic peculiarity. The topaz hue of the primary cannot be so directly associated with the subtraction of particular qualities of light; it is more probably due to an enhancement of that veiling of the higher spectral reaches to which sunshine owes its primrose tinge. Further investigation is, however, desirable; above all, the photographic registration on isochromatic plates of the unfamiliar absorption-bands from which the companion of $\beta$ Cygni derives its distinction as an azure star.

The theory of "composite stellar spectra" was proposed by Professor Pickering in 1891.[3] Spectrographic impressions showing a mixture of types should, he explained, result from the superposition of dissimilar spectra derived from close or telescopically indivisible stars. The forecast was verified by Miss Maury's detection of eighteen self-imprinted images of the compound sort.[4] "In spectra of this class," she writes, "the K-line appears either unduly narrow or overspread with a peculiar haziness. This appears to be due to the presence of an additional star, having a spectrum which belongs to some group earlier in the series. It is also significant that in such spectra the first-type characteristics predominate in the ultra-violet, the second or third-type features in the green and blue." These duplex effects demonstrably own, in certain of the instances enumerated, a duplex cause; for they include $\gamma$ Andromedæ, $\epsilon$ Bootis, and $\alpha$ Piscium, all three remarkable

[1] *Phil. Trans.* vol. cliv. p. 431.
[2] *Bothkamp Beob.* Heft ii. p. 28.
[3] *Astr. Nach.* No. 3034.
[4] *Harvard Annals*, vol. xxviii. p. 93.

pairs. The presumption is accordingly strong that spectra appearing hybrid in small-scale delineations really emanate from a double source, although visual evidence of duplicity be wanting. Indeed, several of Miss Maury's *crypto-doubles*, $o$ Leonis, $o$ Andromedæ, and $\alpha$ Equulei among the number, have been spectroscopically resolved by Professor Campbell into unlike pairs. And even should the motion-test fail, it need not be inferred that the star recalcitrant to it is single; for a negative result may signify merely that the method is inapplicable owing to the high inclination of the plane in which coupled stars revolve.

One of the show-objects of the heavens is $\gamma$ Andromedæ, composed of a chrome-yellow star of 2·2 magnitude, and a sea-green fifth-magnitude attendant at 11″. The attendant itself can be divided with a good telescope into a blue and a green star, considerably advanced along an elliptic track since their first observation by Otto Struve in 1842; while the wide pair, discovered by Christian Mayer in 1777, remains relatively fixed, although their systematic union is attested by an identical secular progress of about 7″. Their spectra, photographed at Tulse Hill, closely resemble those of the components of $\beta$ Cygni, the different patterns of absorption stamped on them forming almost as striking a contrast in the negatives as the colours of the original objects do in the sky. A similar combination is offered by $\epsilon$ Bootis, but on a reduced scale. The ultramarine satellite is here poised at a distance of only 3″ from its golden primary. Their spectra have, indeed, been no more than inferentially distinguished. Miss Maury's scrutiny of the joint impression left by them upon the Harvard plates made it, however, fairly certain that, as usual, the blue star is of Sirian, the yellow star of solar quality; so that a relation of development is again indicated just the converse of that held, on *à priori* grounds, to be probable.

The theoretical incongruity is, in some cases, heightened by the substitution for the sun-like primary of a red star giving a fluted spectrum. Such a pair is $\alpha$ Herculis. An "emerald" star of the sixth magnitude, at a distance of 5″ from its glowing leader-orb, yielded to Sir William Huggins's early examination a spectrum of precisely the same character as that of the satellite to $\beta$ Cygni. Antares, too, is quite

similarly coupled with a green star, the spectrum of which, judging by the duplex impressions obtained at Harvard College, resembles that of Sirius, with, it may be, some approximation to that of Procyon.[1]

Mr. Burnham performed in 1881 the unprecedented feat of dividing a third-type star into a very close pair. He detected a satellite of the ninth magnitude situated within just one second of arc of $\eta$ Geminorum, a fine red star, variable in a period of 229 days, although its maxima are unmarked by any signs of gaseous emission, doubtless because of the comparatively slight extent of the light-change. The spectrum of the small star cannot, of course, be directly observed, but its nature may be indicated by colour-observations. Should a glint of blue or green be caught under favourable circumstances, the inference that it proceeds from a source of the Sirian quality can be unhesitatingly drawn. A particular interest attaches to $\eta$ Geminorum as the only Antarian star with a companion likely to prove sensibly mobile within a reasonable lapse of time.

The spectra of double stars that are unstable in colour have an importance both evidential and explanatory. They illustrate and tend to expound chromatic phenomena. The diversity in light-quality of 95 Herculis is then of extreme significance. These stars, as our readers will remember, are now perfectly matched. They are of equal brightness, and of the same yellow shade. But half a century ago they displayed brilliant complementary radiance in red and green. And their spectra correspond, not to their present uniformity, but to their historic contrast. Vogel in 1899 recorded for one component—presumably the star formerly green—a Sirian, for its twin a solar spectrum. Additional weight is thus lent to the old observations; and a hint, not to be neglected, is given as to the probability of future change.

It is less surprising to meet with spectral dissimilarity in the components of $\gamma$ Delphini. For they differ in magnitude, and very markedly in colour, notwithstanding past intervals of agreement. And it was just during one of their periods of agreement, in 1883, that Vogel found the larger star to be of solar type, while its companion, now green, but then colourless,

[1] A. C. Maury, *Harvard Annals*, vol. xxviii. pp. 92, 100.

gave a Sirian spectrum. Here again, as in 95 Herculis, spectral distinctions seem to persist while chromatic distinctions are alternately effaced and restored.

A good many yellow stars have purplish attendants of dubious spectroscopic standing. Their quality remains untried, and is difficult to conjecture. One of the best examples is $\eta$ Cassiopeiæ, a revolving pair consisting of a 3·5 and a 7·5 star 5″ apart. The primary emits golden light marked with the solar stamp of absorption; its satellite has been variously described as violet, rosy, and garnet. These notes of colour, indeed, supply no hint as to the nature of the corresponding spectrum; but some indication that it is more "advanced" than that of the large star may be gathered from the mass-relations of the pair. Their gravitational disparity, as determined by Otto Struve, is 3·7 to 1, while their light disparity is 40 to 1. In other words, the satellite is nearly seventeen times less luminous than it would be if of the same mean density with its primary, and of equal areal lustre. In reality it is probably both more compressed and less brilliant. But these properties belong to a comparatively late stage of growth, and should be associated with a strongly absorptive atmosphere. The precise type of absorption characterising dependent stars of a violet hue it would be rash to predict, but it is very desirable to ascertain.

A pair closely resembling $\eta$ Cassiopeiæ is $\xi$ Bootis. Again in this case a yellow primary of solar type has a rose-purple attendant actively circulating round it. With it may be classed a couple in Pisces ($\Sigma$ 3036), coloured "very little yellow and dusky red,"[1] and probably $\beta$ Cephei, composed of a sulphur-tinted helium star of 3·4 magnitude,[2] and an eighth-magnitude violet attendant at 14″.

The great majority of double stars present, however, the same or similar tints; they are white and creamy, or sulphur-coloured and golden, and the spectra derived from them accord entirely with these indications. They are almost always variants of one type. But the rule observed in contrasted pairs that the smaller is the earlier star is here inverted. The subordinate members of systems undistinguished

[1] Leavenworth, *Publ. Leander M'Cormick Observatory*, vol. i. pt. iv. p. 96.
[2] A. C. Maury, *Harvard Annals*, vol. xxviii. pp. 17, 119.

for colour often show signs of having progressed further on the road towards extinction than the larger orbs. This principle is finely illustrated by the grand southern binary, *a* Centauri. Now these stars are almost exactly equal in mass, yet one gives only a quarter of the other's light. It is also more deeply tinted with yellow; we may, indeed, safely infer that it is dimmer mainly because of the additional absorption to which its colour testifies. The spectra of the pair, splendidly delineated in Sir David Gill's photographs, are both of the solar class, but with a difference.

That of the brilliant component is an exact copy of the Fraunhofer spectrum (see Plate X. Fig. 2), while that of the inferior star might be called post-Arcturian, manifesting traces of affinity with the fluted type of Betelgeux.[1] The spectral relations of *a* Centauri doubtless prevail in many other systems, but they do not arise inevitably, even under quite similar conditions. Thus the unequal stars of $\gamma$ Leonis give virtually identical spectra of the Arcturian or post-Arcturian species;[2] and the equal stars of $\gamma$ Virginis, though of Sirian type, are unmarked by the smallest difference in the mode of absorption. It would then appear that, while two globes cast, as it were, in the same mould, like those united in *a* Centauri and $\gamma$ Virginis, frequently proceed *pari passu* along the life-course of suns, one may outrun the other under the influence of unknown circumstances. Couples unassorted in size comport themselves differently; but here, too, allowance has to be made for original diversities of constitution, or supervening incidents of development.

To resume. The colours of double stars afford preliminary indications as to the nature of their spectra, but cannot, in all cases, be interpreted with much confidence. Blue and green stars are, as a nearly invariable rule, the satellites of red or yellow primaries. They belong to the Sirian type, modified, probably, by special absorption serving to lend predominance to the more refrangible rays, and so produce their unusual tints. "Purple" attendant stars have also been observed; the quality of light, however, corresponding to this designation

[1] Pickering, *Astroph. Journ.* vol. vi. p. 350.

[2] Huggins, *Atlas of Spectra*, p. 164, plate xii.; Bélopolsky, *Astr. Nach.* No. 3510.

remains unknown. It may prove to be stamped with strong absorption, such as would be symptomatic of advanced condensation; and if so, purplish or violet satellites are a radically distinct class of bodies from azure stars; for they might be inferred to be proportionately more massive and less luminous than their primaries, while the inverse relation doubtless holds good in gold and green as well as in topaz and turquoise combinations. Stellar pairs of equal magnitudes are, with the rarest exceptions, alike in colour and spectrum. They are primrose-tinted—scarcely ever pure white—and of solar or Sirian type.

The spectra of couples no more than two seconds apart can be separately photographed with the Tulse Hill apparatus; and indications of duplicity are often obtained from the composite nature of the spectral impressions given by apparently single stars. Only dissimilar components, however, are capable of being thus distinguished; superposed spectra disclose themselves as such by their differences, among which opposite motion-displacements are occasionally met with. The discrimination of mixed qualities of light in single spectrographic records is a branch of research promising further developments.

# CHAPTER XV.

## THE EVOLUTION OF THE STARS.

The suns of space are subject to the *sic transit* of mortality. The time has been when they were not, and in the time to come they will surely cease to be. The "incorruptibility of the heavens" is no longer a postulate of science; it has been in a measure superseded by the still more antique notion of the "perpetual flux" of things. Creation is a process; it has a history; and the records of its history are not wholly illegible to science.

Those inscribed in the heavens more particularly invite attempts at decipherment. Inquiries into the physical constitution of the stars inevitably lead to them, nay, insensibly merge into them. In the celestial regions, more than elsewhere, we are impelled to read the past and future between the lines of the present. There, by a wonderful course of development, the designs of the Maker are being unfolded, but with such majestic leisureliness that each step represents the lapse of millions of years. To trace even its broad features is, then, a task to be undertaken only with extreme diffidence; yet some few safe principles are available, guided by which we hope not to wander far from the truth.

Long ago it became evident to observation that nebulæ were the matrices of stars. Stars visibly nebulous are then in the earliest stage of growth. So much, at any rate, may be assumed without sensible risk of error. Again, radiating globes necessarily condense with the efflux of time. As heat, the source of their expansive vigour, is dissipated, their particles succumb to gravity, which suffers no waste. They contract; the same quantity of matter occupies in them a

continually diminishing space, and acquires a proportionately more substantial consistence.

The application of these tests gives a concordant result. Both point to helium stars as being at the start of the cosmical procession. They have often nebulous appurtenances; they congregate in nebulous regions; they show with nebulæ spectral relationships of a subordinate, but significant kind. Their mean density, moreover, is known to be extremely small. The conditions of their eclipses, where they form occulting couples, gives the means of assigning to it a fairly definite value; and it appears to be about one-seventh that of the sun. This result is, of course, only preliminary, and cannot legitimately be generalised. It serves, however, to confirm what evidence of a different kind more vaguely indicates.

Helium stars are, then, the most primitive class of suns; and the point of outset being once established, the advance takes a prescribed and inevitable line. We have seen that helium stars pass by the finest gradations into Sirian, Sirian into solar stars, and these again into stars giving fluted spectra. So far there is no breach of continuity. Individual varieties must unquestionably arise, varieties due to minor diversities of chemical constitution, to systemic conditions, to physical influences exerted, possibly, in certain tracts of space; but the great wave of change sweeps on independently of these ripples on its surface.

The order of succession of the four chief stellar families leaves, accordingly, little room for doubt. Our next inquiry relates to the causes of their progressive transformation. We know of two which must be operative—dissipation of heat and augmentation of gravity. The function of a sun is to dispense energy; its distinctive organ, the photosphere, is precisely an apparatus for discharging this function rapidly and effectively; every year of a star's radiation involves, then, a corresponding subtraction from its not unlimited thermal store. Yet this is not necessarily accompanied by a fall in temperature. Gaseous bodies, on the contrary, grow hotter as they cool. This seeming paradox was enunciated by Homer Lane of Washington in 1870. It is now a universally admitted principle of science. What is signified by it

is that the contraction of masses in the gaseous state more than supplies their loss of heat by radiation. It ceases to apply when liquefaction sets in, but we are entirely unable to fix the stage of evolution at which this point is reached. We are only certain that the youngest stars, being unquestionably gaseous to the core, are rising in temperature; their acme is still to come.

But average temperature is not the same thing as surface temperature. The former, in two radiating globes, may be the same, while the latter is very different. For it depends essentially upon the rapidity with which heat can be conveyed outward and upward, and this again is prescribed by interior conditions varying with mass, density, and radiative facilities. Now Lane's law has to do only with average temperature, while spectral indications relate to purely superficial heat-conditions. If we can learn something definite even as to these it will be much; but at present the utmost uncertainty prevails as to how the recorded facts should be interpreted. It seems indeed pretty clear, from the frequent occurrence of "enhanced" lines in the spectra of white stars, both of the Orion and the Sirian kinds, that the state of things in their reversing strata approximates to that in the electric spark, while vapours glowing in the arc represent better the layers absorbing sunbeams and the rays of Antarian stars. But in regard to the essential nature of the difference, authorities are not unanimous. According to Sir Norman Lockyer, Dr. Scheiner, and others, temperature alone is concerned; the spark is hotter than the arc. Intense molecular excitement, due to the disruptive discharge, gives rise to altered modes of vibration, betrayed by substitutions of new spectral lines for those previously visible; and these substitutions, reiterated in the stars, tell emphatically of their enormous temperatures. On the other hand, Sir William and Lady Huggins relegate temperature to a position of secondary importance, and count density the main factor in spectral change, their contention being supported by impressive experimental arguments. Their photographs, too, show some unexpected signs of superior strength of ultra-violet radiation in solar as compared with white stars; and this, if substantiated, would assuredly imply their higher temperature.

For the radiative *centre of gravity* shifts upward with increase of heat, a relation familiarly illustrated by the whitening of red-hot iron before the melting-point is reached.

All of which is exceedingly perplexing; and there is more behind. Gravity is of potent influence in determining temperature. The physical condition of bodies cannot be compared without reference to the scale of their construction, and their spectra vary to correspond. A score of years ago Ritter enunciated the theorem that "the surface temperatures of two stars of equal densities are to each other nearly as the square roots of their masses."[1] And Professor Perry reached quite lately the analogous conclusion that the temperature of a star varies as the product of its age and mass so long as it behaves after the manner of a body gaseous throughout.[2] Further, the superficial heat of stars obviously depends upon the activity of convection-currents in their interiors, and these of course slacken as viscosity increases. This adds greatly to the complexity of the problem, since the transcendental temperature and pressure reigning in the depth of stellar globes must affect in unforeseen ways the viscosity of the materials placed under circumstances outside experience.

Clearly, then, the stars can be arranged in order of temperature only with hesitation and tentatively. If we might accept Ritter's inference that the sun's radiating layer was never in the past, and can never be in the future, at a much higher temperature than that now belonging to it, some difficulties would be removed. For it involves the consequences that the solar type of spectrum marks the culminating point of superficial heat, and that no star can be hotter than the sun unless it contains a larger quantity of matter; and these, if valid, would provide solid ground for classification. But they are highly disputable, and we can only conclude that it is safest not to dogmatise about relative stellar temperatures.

Sir William and Lady Huggins regard as of primary importance in the development of stars the gain of surface-gravity which inevitably accompanies their contraction. They are unquestionably right. Atmospheric pressure varies with

[1] *Astroph. Journ.* vol. viii. p. 307. [2] *Nature*, vol. lx. p. 249.

gravity, and the spectral characteristics of incandescent vapours are affected to an incalculable degree by their density. Every addition to gravitational power, moreover, serves to quicken atmospheric circulation. The tendency to sorting out by the formation of concentric shells of substances differing in atomic weight, is overborne by the uprushing of convection-currents. The strata become mixed, and the heat-gradient becomes steep. These atmospheric modifications are reasonably numbered among the concurrent causes of development from the Sirian to the solar spectral type. They must, at any rate, be concomitants of stellar condensation, unless the path of progress is deflected by unknown agencies. It is well to remember that electromagnetic forces play a part in cosmical evolution—a part deprived of none of its importance by our inability to define its nature. We can only see that they may not be excluded, and await patiently the outcome of future research.

All this refers to the individual history of cooling globes. How, we may ask, does it apply to the relative histories of various globes differing very greatly in mass? The customary answer is that massiveness retards development. That it retards cooling is quite certain, since the larger of two unequal spheres has, relatively, the smaller radiating surface. Hence the old view that change of temperature and spectrum proceeds evenly together had as a corollary that the quicker pace belonged to the lesser star. Spectra of the Orion and Sirian patterns should, accordingly, distinguish orbs on the whole of far more imposing proportions than those giving light of the solar and Antarian qualities. Just the reverse, however, appears to be the case. All practicable modes of comparison agree to indicate that the "mean" solar star sends out a larger sum-total of light from a considerably smaller luminous surface than the "mean" Sirian star.[1] The solar star is, moreover, the denser body, and therefore the more massive in a ratio very much beyond that of its superiority in luminous power.

But the most cogent proof that giant suns develop quickly is derived from the spectra of double stars. The members of binary systems may fairly be regarded as contemporaneous.

[1] Maunder, *Knowledge*, vol. xiv. p. 73.

Their origin was in common; their destinies are indissoluble; they are identically circumstanced; they must be similarly composed. They should then be exceptionally trustworthy guides to the unravelment of evolutionary time-relations. Now they inform us, in distinct terms, that in contrasted pairs the earlier type of spectrum characterises the minor body. The primary being solar or Antarian, the satellite is of the Sirian class. Further, the inequality of mass in such cases is certainly greater than the inequality of light. The small blue star is more tenuous than the reddish luminary it attends. These phenomena enforce the conclusion — the inverse of Ritter's—that stars of the first type are greatly less massive than coeval stars of the second.

Here resides the crux of the evolutionary problem. We have no choice but to believe that the four ages of stellar life succeed each other with relative promptitude in globes built on a great scale. But what looks like an insurmountable difficulty may, on closer inspection, prove a most valuable help towards the establishment of sound doctrine. Sir William and Lady Huggins threw out the suggestion in 1897[1] that "the effect of great mass on surface density, together with the working of Lane's law, will favour the coming in of a solar type of spectrum at a somewhat earlier relative time." They indeed finally rejected the idea;[2] yet it is strongly confirmatory of their own views as to the importance of the gravitational factor in the unfolding of stellar life-history. Rapid atmospheric circulation, indispensable, as they hold, to the production of a solar spectrum, would be set up earlier in *heavy* than in *light* globes; and the requisite adjustment between temperature and pressure should be similarly anticipated. That this is what really happens, we are assured by the prismatic observation of jewel-tinted star couples.

It does not, however, follow that large stars are short-lived. The explanation of the facts just offered involves no such paradox. For it is amply possible that the lesser order of stars may not survive to reach the Antarian stage. They may perish on the way. Extinction perhaps overtakes them while still in mid-career. They may lapse into the ranks of "dark stars" before time has been allowed them to put on

[1] *Astroph. Journ.* vol. vi. p. 326. [2] *Atlas of Spectra*, p. 160.

any recognisable badge of decadence. If this be so, stars with fluted spectra are the outcome of a kind of natural selection. They are bodies endowed with sufficient heat to keep them luminous to the end, while others, having squandered less ample supplies by quicker cooling, sink prematurely into invisibility. This is no idle speculation. The sidereal system is known to include countless non-luminous globes, the origin of which is largely enigmatical. Their obscurity, most likely, dates from various epochs in stellar life. And the smallest masses should, under similar circumstances, cease first from sun-like existence.

So far, account has been taken of only four stellar families, selected as the basis of the evolutionary argument because their mutual relations seem unmistakable. Helium stars are the direct progeny of nebulæ. The formation of a photosphere definitely marks the transition. By the gradual effacement of "Orion" lines they merge into hydrogen suns, these, through the creeping into prominence of innumerable metallic absorption rays, into solar orbs, which finally pass, by successive minute changes, into the fluted stage. But what, we cannot refrain from asking ourselves, lies beyond? Through what phases of decline do great red stars of the Antarian order subside into extinction? No confident pronouncement on the subject is possible, but the conjecture may be hazarded that a stadium of variability precedes the end. Periodic light-spasms perhaps indicate failing vitality. They may eventually die out, and be succeeded by a permanent minimum. Already one such example seems to be afforded by T Ophiuchi, which has for some time ceased from its annual brightenings. Recurrent maxima may, after all, be only flickerings in the socket. This possibility lends a particular interest to research into the causes of these extraordinary outbursts.

Now about the same proportion of carbon stars as of Antarians are markedly variable. Hence, if radiative instability betoken decrepitude in one class, it must do so in the other. It would, indeed, on many grounds, be unreasonable to set the two families far apart in the chronology of the heavens. Professer Vogel regards them as collaterals. They represent, in his scheme, alternative lines of descent towards the final quenching, there being a total absence of evidence

that either has sprung from the other. The pedigree of carbon stars is, in truth, highly obscure. Besides them only one celestial body shows recognisable traces of carbon absorption, and that body is our sun. As effete suns, accordingly, Sir Norman Lockyer ranks these remarkable objects. But the transitional spectra we should expect to meet with, if this were the case, are missing. Solar stars with incipient carbon flutings are unknown. No road runs between the designated stations. A line of communication is wanting. Nor is the development of Antarian into carbon stars easy to admit. A few instances of nondescript banded spectra have, to be sure, been recorded, and might conceivably serve to bridge the gap; nothing, however, resembling an intermediary series can be made out. Now stars without obvious relationships presumably developed quickly under abnormal conditions. And carbon stars seem to be in this case. They must indeed have had progenitors, although none openly claim them. With three stocks, nevertheless, they show distant affinities, and from one or other they must have sprung. Their banded spectrum can be traced in embryo in the sun; their dark-line spectrum is analogous to that associated with Antarian flutings; their bright-line spectrum partially matches Wolf-Rayet emissions. But these are no more than hints towards a genealogy, of which nature still keeps the secret.

There can be no hesitation in placing the Wolf-Rayet and the bright-line helium groups at an early stage of cosmic growth. The Pickering and Rydberg hydrogen lines, which commonly go together, are, for some unknown reason, characteristic of a primitive condition, and they are essential elements of the Wolf-Rayet spectrum. The absence from it of metallic rays is an indication of the same purport; for they are similarly suppressed in nebulæ, while gaining strength and depth in the successive stellar generations. Yet Wolf-Rayet stars are not visibly nebulous. Must we then suppose that they have sprung from stars that are? This is scarcely possible, in view of the peculiarities just adverted to; nor is the admission necessary. Small, compact nebulæ, without hazy appendages, are quite likely, by their condensation, to have given rise to this class of stars. If so, their telescopic sharpness is a necessary consequence of their mode of origin.

But the connecting links have still to be detected. Until they are, the suggested parentage remains an unverified conjecture.

Nebulous attachments, on the other hand, plainly seen or photographed, not unfrequently declare the affinities of bright-line helium stars. They are accordingly at the outset of their careers as suns—that is to say, they have given since the time when they were first formed into powerfully radiating globes the same kind of spectrum now exhibited by them. It will, however, eventually become modified; and the most probable modification to which, so far as our limited view extends, it can be subject, is by the disappearance of its specific rays of emission. Their progressive effacement might plausibly be represented by a series of objects, in which linear radiation grows less and less, from $\gamma$ Cassiopeiæ, with its full complement of bright lines, down to Alcyone, showing a solitary C. Yet this would not compel the admission that every dark-line helium star has traversed a bright-line phase. Such an episode, on the contrary, can be inferred from many indications to occur by exception in stellar history as a consequence, perhaps of peculiarities of internal constitution, perhaps of unusual influences exerted from without, possibly of the mutually reactive effects of both classes of cause.

We must be prepared to meet with side-tracks in evolution. Nature does not run in a groove. Her operations are free and various; they defy the restrictions of feasibility which a rigid methodism of thought would seek to impose. The order of the universe has a wider scope than is imaginable by us. Creative Wisdom disposes of superabundant resources, and, if we may dare say so, takes delight in bringing them into play. Our best attitude of mind, then, in attempting to speculate on the course of things, is that of the utmost possible flexibility to the teaching of well-ascertained facts.

# CHAPTER XVI.

## ROTATION OF THE STARS.

SIR WILLIAM ABNEY adverted, in 1877,[1] to the theoretical effects of rotation on stellar spectra. Quite obviously, they must tend to make the component lines wide and diffuse. For each line integrates the displacements and counter-displacements occasioned by the opposite radial movements of the limbs; while the central and polar sections of the disc, having their velocities directed across the line of sight, send out rays in their normal positions, fringed on either side through the juxtaposition of the shifted rays. The amount of broadening in each particular star depends, first, upon the linear speed of rotation, secondly, upon the position of its axis. If this be erect as viewed from the earth, the motion-shifts will tell to their full extent in spreading the bright or dark spectral lines; they will become less and less effective as the axis is less inclined, and will disappear wholly on its coincidence with the visual ray. Now there can be no doubt that every star has a movement of gyration as well as a movement of translation; and it is no less certain that stellar spectra are modified in accordance with its rapidity and direction. Only the question of degree has to be considered. Are the effects produced likely to be appreciable? And if so, have they been perceived?

The spectrum of $\alpha$ Aquilæ (Altair), noticed for some time back as peculiar, has sometimes been thought to intimate a composite origin. It is of the Sirian type, but with a reinforced contingent of metallic lines; and these run

[1] *Monthly Notices*, vol. xxxvii. p. 278. The difficulties in applying the theory were pointed out by Vogel, *Astr. Nach.* No. 2141.

together into hazy bands, the general aspect of which was imitated at Potsdam in 1895 in spectrographs of the sun taken out of focus.[1] The defective nature of the agreement, however, discredited the hypothesis of a double spectrum, marked by diffuse hydrogen absorption proceeding from one source, and by metallic lines *fused* into bands, proceeding from another. Yet M. Deslandres considered that his measures of the star's radial motion lent it support. They seemed to indicate velocity variable in a period of forty-two days, with minor fluctuations superadded.[2] But the supposed multiple system is, according to Dr. Vogel, a mere creation of accidental errors,[3] and *α* Aquilæ must for the present, at any rate, be counted a solitary star.

Its spectrum was, in 1893, commented upon by Professor Pickering.[4] He had recourse, for the explanation of its ill-defined character, to the rotational principle, adding a caveat based on the improbable greatness of the required velocity of about 100 miles per second. Adopted, nevertheless, five years later by Dr. Vogel, it was rendered more plausible by his reduction to 27 kilometres (16·8 miles) of the equatorial speed needed to widen the lines to the observed extent. This rate of movement, which is just double that of a point on Jupiter's equator, might reasonably be admitted as subsisting in a star. But the view encounters other, and more fundamental objections. If it were true, *all* the lines in the affected spectrum should be similarly diffuse. Movement acts indiscriminately. Every ray emanating from the advancing or receding surface is, in due measure, displaced. None can be exempt from change of refrangibility. The occurrence, then, of a single sharp line in a stellar spectrum suffices to show that the haziness of its associates must be due to some other cause than rotation. And there are many sharp lines in the spectrum of *α* Aquilæ. They are faintly discernible, as Sir Norman Lockyer pointed out in 1894,[5] on the South Kensington plates, and are

[1] Scheiner, *Astr. Nach.* No. 2924; *Potsdam Publ.* Bd. vii. p. 232.
[2] *Comptes Rendus*, t. cxxi. p. 629.
[3] *Sitzungsberichte*, Berlin, 17th Nov. 1898.
[4] *Astr. and Astrophysics*, vol. xii. p. 719.
[5] *Phil. Trans.* vol. clxxxiv. p. 696.

unmistakably apparent in Sir William and Lady Huggins's spectrographs.[1] Those taken at Potsdam are so limited in range of wave-length that negative conclusions cannot safely be founded on them. The hypothesis of rotation must, accordingly, be regarded as inapplicable to the case of *a* Aquilæ.

Now *a* Aquilæ is not without analogues. It belongs to a pretty numerous stellar group, differing in chemical constitution, but agreeing in the diffuseness of the absorption traits significant of it. They form one of Miss Maury's three collateral series—her "Division *b*." It embraces no "advanced" stars; only those of the helium and hydrogen types, with a few verging towards the intermediate stage of Procyon, are represented in it. Hazy spectra are thus a sign of cosmic youth. They characterise, without exception, the stars of Miss Maury's "Group i.," in which the Pickering series of hydrogen is prominent; they cease to appear, or appear by imperfect indications, soon after the Sirian stage is passed. Their explanation by opposite displacements through axial movement would then involve the consequence that stars, as they develop, lose much of their rotational speed. There is, however, but one recognised agency by which it can be retarded—the agency of tidal friction; and it acts sensibly only on bodies attended by closely-revolving satellites of considerable relative mass. Solitary suns like our own can have spent but little of their energy of rotation. Actual velocity in spinning becomes, in fact, accelerated as contraction proceeds, so that ageing stars should have their spectral lines more broadened by motion than those in a primitive condition. And since the effect is imperceptible in the former, we may feel assured that it has not been observed in the latter.

Confirmatory evidence is not wanting. There is a certain class of stars which, we have the strongest reason to believe, rotate in very short periods, and on axes almost perpendicular to the line of sight. They combine, accordingly, both the conditions needed for the display of spectra rendered diffuse by motion-shifts. These are occulting variables like

[1] *Atlas of Spectra*, Plate ix.

Algol. Since they revolve in planes passing very nearly through the earth, and their equators cannot deviate materially from the same level, it is certain that virtually the whole speed of their advancing and receding limbs is radially directed; no considerable part of it is spectroscopically ineffective. Further, although they may rotate faster, they cannot rotate more slowly than they revolve, and their orbital periods are extraordinarily short. The system of Algol, which is by no means one of the quickest eclipsing pairs, circulates in sixty-nine hours. Its equatorial rate of rotation, by a minimum estimate, is thirteen miles a second, or just eleven times the solar. The absorption rays in the light from one limb are accordingly displaced towards the blue, and those from the opposite limb towards the red, eleven times more than the Fraunhofer lines measured by Young and Dunér; and their compounded effect in the stellar spectrum is to widen the lines by an amount corresponding to a speed of twenty-six miles. In other words, each should spread over nearly one quarter the interval between the D-lines in the sun. The alteration is, nevertheless, inconspicuous. The spectrum of Algol does not strike the eye as hazy. The hydrogen series shows the distension proper to the type, no more; the rays of helium, magnesium, and calcium are of the average sharpness. Now some eclipsing stars must rotate much more rapidly than Algol. U Ophiuchi, for instance, has a period of only twenty hours. Yet in none of them have blurred spectra been noticed. Enormous velocities — velocities most probably non-existent — would evidently be indispensable for their production.

Such spectra as that of *α* Aquilæ must then be accounted for otherwise than by rotation. For the suggested geometrical cause, which proves inadequate, a physical cause has to be substituted. One may be found in excessive pressure. The diffuse lines possibly originate at unusual depths in the stellar atmospheres. Sir William and Lady Huggins advert [1] to the probability of great differences in this respect between various stellar classes. In early stars they say—and none of the members of "Division *b*" are mature—"we may see deep down into the star, and the continuous spectrum may come

[1] *Atlas of Spectra*, p. 69.

from a thick region of dense gas, throughout which little, or possibly no condensation to the liquid or the solid state takes place. Under these conditions, the absorbing gases in front of it will not be, as in the sun, of very limited thickness, but will occupy a region of vast extent."

The solar H and K illustrate the character of lines generated in dense vapours at a high temperature; their "wings," as we may remind our readers, being added in the immediate vicinity of the photosphere to the comparatively definite lines produced in the upper reversing strata. Now it is a curious fact that distended lines, such as H and K, are apt to be doubly reversed. Dr. Scheiner has noticed symptoms of incipient illumination at the centres of the broad hydrogen bands distinctive of first-type stars, and they are similarly manifest in Wolf-Rayet stars showing mixed series of emission and absorption. Hence the particular significance of M. Deslandres' detection in *α* Aquilæ of fine "chromospheric" lines of hydrogen, and occasionally of calcium and iron,[1] superposed upon the dim, dusky bands indicative of the state of those substances in the reversing layer. Diffuse spectra may thus, with some probability, be assigned to abortive bright-line stars. Or they perhaps mark objects just losing the faculty of specific emission. If so, the mode of its departure is different from that exemplified by Alcyone, in which the dark lines have their normal aspect, while one red ray survives as the sole remnant of what was perhaps once a blazing spectrum. The future course of stars resembling *α* Aquilæ can be traced only by conjecture. But what hints are at hand lead to the supposition that they will proceed by insensible gradations to the solar stage, their absorption rays becoming narrower, more numerous, and better defined with the slow advance of condensation.

The upshot of our inquiry is to bring the conviction that no approach has yet been made towards determining the rotation of any star. Spectra are not rare composed mainly of blurred lines, and so suggesting at first sight diffusion on the principle of movement; the intermixture of sharp lines, visible on closer scrutiny, nevertheless peremptorily negatives the suggestion. Again, rotational velocity in the line of sight

[1] *Comptes Rendus*, t. cxxi. p. 629.

should be at a maximum in Algol variables; yet they do not possess specially diffuse spectra. Theory, however, need not be at fault because it fails to be verified by observation. The failure merely informs us that its consequences, by their smallness, elude our means of discovery.

# CHAPTER XVII.

## SPECTROSCOPIC BINARIES.

BETWEEN the old and the new astronomy lies a region claimed by both, yet belonging by exclusive right to neither. This is the department of spectroscopically determined, or radial movements. Now the distinction between radial and transversal movement is purely artificial; it is made in the interests of our imperfect faculties; nature ignores it. Motion, although by a geometrical fiction resolvable *ad infinitum,* is essentially simple. At any given instant it takes place in one direction only. But if that direction be oblique to our view, we see the line of travel foreshortened; nor can we tell by direct vision how much foreshortened. That is to say, the eye perceives one component of velocity—the tangential component, the component lying square before it—while of the other component along the visual ray it takes no heed. Here the spectroscope comes to the rescue. Helpless to deal with tangential speed, it can measure radial speed by its effects upon the refrangibility of light. The first method gives one side of the parallelogram of velocities, the second, the other; combining their results, we get the diagonal actually traversed by the observed luminous body. Data obtained by visual means formed the sole materials of the elder gravitational science; none others were indeed available at the period of its growth and elaboration; nor, even if they had been, would they have been of essential service in constructing planetary theories. In sidereal astronomy they occupy quite a different position. Without them its progress is crippled, and the possibility of procuring them fortunately developed just when they began to be urgently needed.

As grist for the mathematical mill, motions determined spectroscopically serve equally well with motions determined telescopically. The calculus deals indifferently with either kind. The calculus, however, is an instrument of precision, and demands minute accuracy in the materials operated upon. And it is just the effort to satisfy this demand which has broken down the barrier between celestial mechanics and celestial physics. For radial velocities cannot be unadvisedly accepted; the line-displacements significant of them may be otherwise occasioned. Cases have to be discriminated; conditions scrutinised; recondite problems attacked. The information within reach is, nevertheless, too important to be neglected; at any cost of pains it must be extricated from uncertainty and used for all that it is worth; and so it has come about that traditional astronomers of the most abstract type find themselves involved in experimental difficulties, and confronted by questions answerable only in the laboratory.

Astrophysicists, on their side, have no choice but to cultivate the spectroscopic branch of dynamical astronomy. Not merely because it springs from the stem of physical principles and physical experience, but because the study of its subject-matter is essential to the furtherance of knowledge respecting stellar constitution and development. Thus sidereal physics merges into sidereal mechanics; yet somewhere between them a line of demarcation must, for the purposes of the present book, be drawn. Arbitrarily drawn in many places it will be; but there are cases in which it is better to lack logic than limit; and this is one of them. We shall then regard spectroscopic but not telescopic binaries as making part of our subject, although fully aware that the two classes are fundamentally one. Stellar and nebular proper motions, transversal or radial, must also as such be excluded. Only when they give evidence, by periodic variability, of the progress of orbital revolutions, do they fall within our scope. Uniform velocities in space, in whatever direction, or however determined, do not concern us. Foreign to our theme as well, is the grand topic of sidereal construction, prescribed as it is and conditioned by the flittings of the stars. Something, however, will be said about the physical peculiarities of the Milky

Way, since apart from them the spectroscopic relations of the various families of stars and nebulæ would remain imperfectly intelligible.

Spectroscopic binaries are stars telescopically single, but inferred to be compound from the evidence of a regular flow of spectral change. The change is of a perfectly definite nature. It consists in the swinging of all the bright or dark lines to and fro in a fixed period across their average positions. These, indeed, are not precisely their normal terrestrial places. They are affected by the motion of the system, as a whole, towards or from the eye. This constant element of shifting is, however, easily eliminated, and the circulating pair can then be studied as if their centre of gravity were at rest relatively to the sun. Ascribing to them, to begin with, a circular orbit, it is easy to see that, at two diametrically opposite points—the extremities of the line of conjunction—radial motion vanishes, the entire measurable velocity being across the direction of view; while at the corresponding points of greatest elongation, the radial component represents full speed. In an elliptic orbit these four points of zero and maximum line-of-sight movement may be slightly displaced according to the situation of the major axis; they can, however, be located with the help of exact observational data, and their positions then serve as an index to the shape and orientation of the ellipse. One of its elements, nevertheless, remains incalculable. Unless the revolving stars eclipse one another, there is no means of determining its plane. It cannot be perpendicular to the line of sight, for in that case all the motion would be tangential; no part of it could be spectroscopically apparent. But it may be inclined at any angle short of a right angle; and the larger the angle, the smaller the proportion of the orbital velocity directed along the visual ray. In other words, the measured rates are the true rates multiplied by the cosine of an unknown angle. They are, accordingly, minimum values; the actual speed indefinitely exceeds them. Nevertheless, it can rarely be more than double the seeming amount, since the chances of discovery manifestly fall off for systems with highly inclined planes. Thus the scale of orbits computed from spectroscopic data is indeterminate; but the uncertainty does not extend to their form, which is as strictly derivable as

that of the paths of visible binary stars.[1] The mass of the revolving bodies, however, escapes us. It depends upon the compass of their rounds; we can only assign to it a value less than which it cannot be, although it may be considerably greater.

Spectroscopic binaries are broadly divisible into three classes: those that are constant in brightness, those that vary in light through eclipses, and those that vary in light otherwise than by eclipse. In the present chapter we shall confine our attention to the first category. And here again we have to distinguish between stars with bright, and stars with dark companions. In the spectra of bright pairs the lines split into doublets twice in the course of each revolution; in those of bright and dark pairs they execute a complete vibration simultaneously with the description of a circuit, but remain always single. But these different conditions are not sharply separated. As usual, the rule of continuity is observed. Satellites are met with in all gradations of luminosity. Some shine no less brilliantly than their primaries, in which case the duplicated lines are exact pairs; others are large but dim, and show very faint rays periodically appended to the comparatively intense ones of the greater orb; while the majority, remarkably enough, are quite obscure, so far at least as spectral indications enable us to judge.

These marvellous systems have, one and all, been discovered by spectrographic means. The required consistency and certainty of measurement are unattainable visually. They have been realised only by the employment of chemical impressions comparable night by night and year after year. The first result of the kind was achieved at Harvard University by the detection as a close double of $\zeta$ Ursæ Majoris, the middle star in the Plough handle. The components are Sirian suns of the same stamp, and of nearly equal brightness; but they may be to some extent relatively variable.[2] The nature of their movements was long an enigma. The period of 104 days at first assigned to them implied

[1] The method usually employed is that given by Lehmann-Filhés, *Astr. Nach.* No. 3242.

[2] A. C. Maury, *Astroph. Journ.* vol. viii. p. 174.

duplication of the spectral lines once in 52 days. Yet this consequence did not ensue in fact with the inevitableness exacted by theory. Grave discrepancies became manifest; the anticipated separation of the two spectra, often non-apparent, was always curtailed in duration, and repeated attempts were baffled to get rid of these anomalies by adding a third body to the system, by heightening the eccentricity of the ellipse traversed, or by shortening the period of its description.[1] At last, in 1901,[2] by a discussion of a fresh series of Potsdam spectrographs, Dr. Vogel reached a satisfactory conclusion. He now assigned to the revolving couple a period of only 20 days 14 hours; the eccentricity of their orbit came out $=0{\cdot}5$, so that their periastron-approach is one-half their mean distance; while their least possible mass proved to be four times that of the sun. Up to the present they seem inclined to conform to these rules of the road.

The parallax of $0{\cdot}045''$ found by Klinkerfues for Mizar (to give $\zeta$ Ursæ its Arabic name) is likely to be largely erroneous, but erroneous by excess rather than by defect. If it be correct, the star sends abroad thirty-eight times more light than our sun. If it be too large, the star is proportionately brighter; and, judging by Höffler's estimate [3]—certainly a most precarious one—it is greatly too large. Since the components are spectroscopically unlike the sun, the ratio of the quantity of light they emit to the quantity of matter they contain must be widely different. Were it the same, a 38-fold brilliancy would imply their possession of about 160 times the solar mass; whereas Vogel's data almost enforce the belief that this value at least decuples the truth. This may serve to exemplify the difficulty of deducing massiveness from luminosity. Only in exceptional cases can any fixed proportionality be safely assumed as the basis of calculation.

Mizar is attended visibly as well as invisibly. A star of the fourth magnitude circulates round it at a distance of $14''$ with an almost imperceptible progression. Unless it mends its pace, 10,000 years will have elapsed before a revolu-

[1] *Harvard Annals*, vol. xxvi. p. xviii.; *Harvard Circular*, No. 11; *Astr. Nach.* No. 3017; *Monthly Notices*, vol. l. p. 297.

[2] *Sitzungsberichte*, Berlin, 2nd May 1901; *Astroph. Journ.* vol. xiii. p. 324.

[3] *Astr. Nach.* No. 3456.

tion is completed. It may be worth recalling that on 18th April 1841, Mädler was unable to find this object, ordinarily plain to be seen; and the failure seemed so strange that he endeavoured to account for it by supposing the star subject to sudden obscurations like those of Algol.[1] No second disappearance is on record; but phases of the kind are extremely evasive when no time-bill of their recurrences is at hand. The connection into one system of two close pairs is not in itself improbable, although no such arrangement has yet been anywhere verified.

The detection of a second spectroscopic binary followed immediately upon that of the first. Miss Maury announced late in 1889, as a result of her scrutiny of the Harvard plates, that the absorption lines in the spectrum of $\beta$ Aurigæ appear alternately single and double once in forty-eight hours. Hence the period of revolution is four days, while the relative velocity of the components, given by the extent to which their spectral rays separate, is 150 miles a second. Their joint orbit has been computed by Rambaut,[2] Lehmann-Filhés,[3] and Schwarzschild[4] so accordantly as to leave little room for improvement. They find its eccentricity to be somewhat less than that of the orbit of Mercury; the major axis makes an angle of 32° with the line of sight, and the periastron is at the end farthest from the earth. The plane being unknown, its dimensions, as already explained, cannot be ascertained. If indeed the observed velocity were the true velocity,—that is, if it lay in a level passing through the eye—the corresponding orbital radius would be 7,500,000 miles, and the mass of the system would rather exceed that of $4\frac{1}{2}$ suns;[5] but these are only the least possible values; they may be greatly surpassed. The components of $\beta$ Aurigæ shine with the Sirian quality of light; they are almost perfectly matched, reciprocal variability, according to Miss Maury,[6] causing each in turn to appear the brighter. A parallax of 0·062″ was photographically determined for them by Professor Pritchard. At the distance indicated, the sun would seem twenty-eight times

[1] *Comptes Rendus*, t. xiii. p. 438; quoted by Gore, *Knowledge*, vol. xii. p. 201.

[2] *Monthly Notices*, vol. li. p. 316.

[3] *Astr. Nach.* No. 3242.

[4] *Ibid.* No. 3629.

[5] Vogel, *ibid.* No. 3017.

[6] *Astroph. Journ.* vol. viii. p. 173.

less bright; it would sink to the paltry status of a 5·6 magnitude star. If $\beta$ Aurigæ were a single globe, constituted like the sun, and giving out a twenty-eight-fold supply of light, it should be of 147-fold mass. Neither of these conditions is fulfilled; and allowance for their realisation might possibly bring into fair agreement calculations of mass from gravitational and from photometric data. In which case the plane of revolution would deviate but slightly from that traversed by the line of sight.

The preceding star of two named $\mu$ Scorpii was disclosed as compound in 1896 by Professor Bailey's notice of the doubling of its spectral lines on many of the Draper Memorial negatives.[1] The period is only 34 hours 42 minutes; the velocity is correspondingly high. By their wide separation the lines tell of relative movement at the rate of 286 miles a second, this being the sum of the opposite velocities of the conjoined bodies. Their orbit, apart from the foreshortening effect of its inclination, has a radius of nearly 6,000,000 miles, and they possess at least fifteen times the gravitating power of the sun. They show a helium spectrum; and one member of the pair is not only fainter than the other, but fainter, apparently, in a variable degree.

The spectrographic method employed at Harvard supplies evidence of line-duplications, but none of the shiftings of solitary lines. This is easily understood. The dispersing apparatus is placed in front of the object glass; the stellar images formed at its focus are then ready-made spectra. Hence no slit is required, and without a slit no comparison-spectrum can be availed of. Displacements therefore betray themselves only when the rays furnish standards of mutual reference by splitting into pairs. The binary nature of stars both bright is, accordingly, discoverable in this way, but not the association of a bright with a dark body.

The spectroscopic discovery of these remarkable combinations was initiated at Potsdam. Dr. Vogel[2] in 1890 found the brilliant Spica ($\alpha$ Virginis) to have its spectrum shifted to and fro once in four days, the revolutions thereby intimated proceeding at the rate—apart from perspective abridgment—

[1] *Harvard Circular*, Nos. 11, 21.

[2] *Sitzungsberichte*, Berlin, 24th April 1890; *Astr. Nach.* No. 2995.

of fifty-seven English miles a second. This implies, if the components be of equal mass, a distance for each from their common centre of gravity of 3,100,000 miles, and a joint mass 2·6 times that of the sun. The spectrum is of the helium type. Sir David Gill obtained a null result for the parallax of the star, which must accordingly be of amazing actual splendour. The attendant of Spica is not wholly obscure. Traces of its spectrum can be perceived, although too faintly for purposes of exact measurement. The couple might then be termed a linking instance between systems composed of twin suns, and those consisting of a luminous and a non-luminous member. The conditions of observation are not only more arduous in the latter case, but the data within reach prove less adequate. They are one-sided; they relate exclusively to the bright star. All that can be learned about its dark companion is that it describes, in the same period, a similar orbit. The size of the orbit is left vague. It is large if the mass of the body traversing it is small, and *vice versâ*; and the mass of the primary is involved in the same uncertainty.

A peculiarly interesting bright and dark couple was brought to notice in 1896 through M. Bélopolsky's work with the thirty-inch Pulkowa refractor.[1] Castor, the lucida of the constellation Gemini, was the object of his researches; and it dominates a system no less wonderful than that of ζ Ursæ Majoris. Two lustrous Sirian stars, of second and third magnitudes respectively, wheel slowly at an interval of 6″. Although they have been wards of science since Bradley's measure of them in 1719, their orbit is not yet, in any strict sense, calculable. It is, however, certainly very eccentric, and takes many centuries to describe. A small, distant star shares the proper motion of this majestic pair, and is hence known to form with them a ternary combination, which the spectroscope has rendered quaternary by assigning an invisible satellite to the minor component of the original binary. Its revolutions are rapid; they have a period of not quite three days, and its gravitative power suffices to impart a radial velocity of 22 miles a second to the luminous orb in its vicinity. The corresponding distance from the centre is 1,800,000 miles;

[1] *Astroph. Journ.* vol. v p. 1.

but this, as in all such cases, is a minimum value. The ellipse traversed is slightly more eccentric than the path of Mercury round the sun. And here arose a curious complication.[1] Obviously, the interval between two periastron passages should, if the major axis remained fixed in space, be identical with the time occupied in making the circuit from node to node. It proved, nevertheless, to be notably longer, and the hypothesis was, so to speak, compulsorily adopted that the major axis shifts forward as the stars revolve. The period of the inequality, as determined by Bélopolsky in 1899, is 2100 days. In four years and forty days the orbital axis makes a complete gyration, and is once more directed as at first. The cause assigned for the disturbance is the spheroidal form impressed upon the conjoined bodies by their reciprocal tide-raising power. A flattening of one-seventh would suffice to produce the observed effect, admitting that the system has the same dimensions as that of Algol. This special kind of perturbation, long theoretically recognised, has been found practically operative only within the narrow precincts of close stellar systems. Its continued study in them may lead to important developments.

The disclosure of a duplex character in Capella was eminently unexpected. Its reputation as an exemplary solar star, irreproachably regular in its movements, had been established at Potsdam, where the spectrographic investigation of radial velocities was set on foot in 1888.[2] But the instrumental resources then at Professor Vogel's command were inadequate to bring out certain deviations from the Fraunhofer pattern lately noticed. The spectrum is indeed both oscillatory and compound; but a powerful and perfect apparatus is required for the manifestation of these singularities. The discovery was, nevertheless, made in duplicate by Professor Campbell at Lick,[3] and by Mr. Newall at Cambridge.[4] It is of unique interest.

Capella is one of the very few spectroscopic binaries at a

[1] *Memorie degli Spettroscopisti Italiani*, vols. xxvi., xxviii.; *Bulletin de l'Acad. des Sciences*, St. Pétersbourg, t. vi. No. 1, t. viii. No. 2.

[2] See *Observatory*, vol. xxiii. p. 127.

[3] *Astroph. Journ.* vol. x. p. 177; *Observatory*, vol. xxiii. p. 92.

[4] *Ibid.* vols. xxii. p. 436, xxiii. p. 93; *Monthly Notices*, vol. lx. p. 418.

determined distance from the earth. The carefully revised parallax of 0·081″, implying a light-journey of forty years, assigned to it by Dr. Elkin in 1897, has every mark of authenticity. Located thus remotely, our sun would appear as a star below the fifth magnitude; 102 orbs like it should be combined to give the light of Capella. Hence the joint volume of the components, assuming them to be equal globes of solar intrinsic brilliancy, must be just 730 times that of the sun. And their joint mass should be even proportionately greater, unless the tremendous force of internal compression proper to bodies so gigantic were counterbalanced by exorbitant heat. There is strong, if not convincing evidence that this is actually the case.

The members of the Capellan system are unequally luminous, and differ in their absorptive qualities. One is spectroscopically indistinguishable from the sun, the other, of about half its brightness, is more akin to Procyon. It has, accordingly, been found possible to measure separately the swing of each set of lines, and they have proved to be of much the same amplitude. This means that the two bodies are animated by equivalent movements, and are hence nearly equal in mass. Their revolutions proceed in a slightly eccentric orbit, the mean radius of which, if seen edgewise, would measure 52,000,000 miles. It is not, however, seen edgewise; very far from it. Capella possibly makes an exception to the rule that the circulatory plane of non-eclipsing spectroscopic pairs is unascertainable; and for this reason, that it may be, to some extent, a visual pair as well. Mr. Newall adverted to the probability, based upon the star's parallax and conditions of movement, that the distance between its components would subtend from the earth an angle of nearly one-tenth of a second. Telescopic observations might then have a successful issue; and the opportunity for testing the powers of great instruments was, at any rate, too tempting to be neglected. Those of the Lick refractor, strange to say, though employed with all Professor Hussey's skill, failed to answer the demand made upon them. The star was seen persistently round.[1] Yet Messrs. Dyson and Lewis were persuaded of its genuine elongation with the Greenwich twenty-eight-inch equatorial. The components were never

[1] *Astr. Journ.* No. 484.

seen clearly divided; no thread of dark space was perceptible between them; but they formed together an oval image, and the direction of lengthening changed consistently with the period of their mutual circulation.[1] The visual data thus procured even served for the calculation of a provisional orbit, and the missing element of its inclination proved to have a value of 30°. The stars, if this be so, travel in a plane making an angle of 60° with the line of sight, and the actual radius of their path is double that derived from spectroscopic velocities. It measures 104,000,000 miles; these immense bodies are not much farther apart than the earth is from the sun. Their mass can hence be arrived at; together they contain somewhat more matter than seventeen suns. This result, though in many ways plausible, is extraordinarily discrepant from what we may call the light-value of the same element. If they gravitated in the proportion of their luminosity, these orbs, as we have seen, should outweigh the sun 730 times; in point of fact, they seem to possess no more than seventeen times the solar mass. Even apart from the Greenwich results, we seem here to find evidence that stars differing enormously in density may show spectra of the same stamp, and that large bodies traverse the various stages of development more rapidly than small. The members of the Capellan pair, admitting the alleged facts, are some forty times more rarefied than the sun; liquid hydrogen is a heavy substance compared with them. They are, accordingly, at an early epoch of their career as radiant globes, while their spectra indicate full maturity. Confirmation is thus afforded to the inference, already drawn from the spectral diversities of double stars, that mass accelerates evolution.

Late in 1896 Professor Campbell undertook at the Lick Observatory a comprehensive investigation of stellar radial motion. The adjustment of the fine apparatus known as the "Mills spectrograph" to the great refractor made this feasible; and among its "bye-products," the analysis of visually single stars into revolving pairs is particularly important, first, because of the individual interest of the facts collected, next, on account of their significance in the scheme of the Cosmos. The abundance with which such systems occur is quite

[1] *Monthly Notices*, vols. lx. p. 595, lxi. p. 70.

unexpected, and very remarkable. Professor Campbell finds that, of 285 stars observed by him, more than one in nine is a spectroscopic binary.[1] And this excludes several objects suspected, but not demonstrated to belong to the same class, and makes no allowance for those cases in which the orbital plane is so nearly vertical that movement in it makes no appreciable spectroscopic effect. He has then good reason for holding it probable "that at least one star in five or six will be found to be a spectroscopic binary," and he is quite prepared "to see a still larger ratio established. The proven existence," he adds, "of so large a number of stellar systems differing widely in structure from the solar system gives rise to a suspicion, at least, that our system is not of the prevailing type of stellar systems. The new field of astronomical research thus opened up is of great richness, and may well occupy the attention, for an indefinite period, of the large number of observers and institutions now engaging in its development. It is perhaps unnecessary to say that the measure of success attainable is dependent upon the degree of accuracy realised in the observed velocities."

The Lick results in this branch are in several respects noteworthy.[2] They show the wide diffusion of arrangements strange to experience, if admissible in speculation. They serve, by the variety of periods which they indicate, to narrow the lacuna between stars directly seen, and stars inferred from Doppler's principle to be revolving. They have rendered it obvious that no generic distinction separates the two classes. A pair revolving in $2\frac{1}{2}$ years, like $\eta$ Pegasi, cannot be set apart fundamentally from $\delta$ Equudei, with its period of 5·7 years. It is, indeed, clear that spectroscopic and telescopic binaries differ only in the mode of their observation; not what they are in themselves, but the aspect under which we regard them, has caused them to be artificially disconnected. Already, however, a tentative beginning has been made with Capella in the telescopic observation of spectroscopic couples; and spectroscopic determinations of orbital speed, long a desideratum for visual pairs, have been tried with good promise

[1] *Astroph. Journ.* vol. xiii. p. 89.

[2] See Appendix, Table II., for a list of the spectroscopic binaries discovered down to the middle of the year 1902.

of success. Individually, too, the detections announced from Mount Hamilton are frequently curious and suggestive. Thus Polaris claims the attendance of two dark companions; while the bluer component of $\kappa$ Pegasi, besides circulating visibly in a period of 11·4 years, circulates invisibly in six days. Again, the primary of the classic pair, $\xi$ Ursæ Majoris, proves to have a variable radial movement, the conditions of which invite investigation. The duplicity of $\upsilon$ Sagittarii is significant for a different reason. The spectrum of this star includes bright hydrogen lines; it was noted by Miss Maury[1] as compound, and perhaps mutable. Motion-displacements, giving a velocity-range of about twenty-five miles a second, were measured in it by Professor Campbell in 1899; but their period remains undetermined, as well as the extent to which they are shared by the responsive lines of the companion-spectrum.[2] For in this case both the stars are luminous, and both show absorption of the helium type. The exceptional constitution of $\upsilon$ Sagittarii, indicated by its emissive symptoms, accentuates the interest of its systemic relations. It should accordingly be an object of particular and persevering attention. Indeed, each of these wonderful pairs may be expected to develop peculiarities of its own, demanding study by varied, and perhaps recondite methods.

[1] *Harvard Annals*, vol. xxviii. p. 104.

[2] *Observatory*, vol. xxiii. p. 128 (A. M. Clerke).

# CHAPTER XVIII.

## ECLIPSING STARS.

Stellar eclipses are necessarily included among the phenomena of spectroscopic binaries. For the planes of a proportion of these systems must pass through the earth, with the result that the circulating bodies occult one another when they cross the line of conjunction. The circumstance is particularly valuable as supplying a datum unattainable with the spectroscope for star couples differently conditioned. The rapid loss and recovery of light which tell us that one body is passing in front of the other, tell us, at the same time, that they revolve in an orbit seen edge on—that is to say, making an angle of 90° with the "tangent plane" of the sphere. Radial velocities are, accordingly, measured in their true proportions, and the masses of stars giving double spectra become strictly determinable. The duration of eclipse, moreover, indicates the density of the obscured and obscuring globes; and where the dimensions of even one of their orbits is known, it supplies a measure for their actual diameters. Thus precise evaluations of the light-changes and radial velocities of these singular objects go hand in hand; both kinds of research are equally necessary to the advancement of knowledge concerning systems which are peculiarly interesting because they are, more than any others in the sidereal world, accessible to investigation.

The circumstances of stellar eclipses are endlessly varied, and their differences are full of meaning. They are central when the orbit is directed straight towards us; they are partial when it deviates from coincidence with the line of vision. Then the interposing body may be dark or bright;

it may be larger or smaller than the globe behind it. Supposing it to be sensibly obscure and the transit central, the eclipse will be either total or annular. The first case is not known, although quite likely to occur; no complete periodical disappearances have been witnessed. The second has not been definitely attested. Its inevitable indication would obviously be a stationary minimum. While the two discs are superposed, the light must remain steadily at its lowest level; and if the eclipse be annular, the discs are, *ipso facto*, superposed during an appreciable interval, the length of which bears an inverse ratio to the depth of the obscuration.

While a bright and dark pair can undergo but one eclipse in each revolution, two are the portion of a couple radiant in both its members. If they are alike in size and brilliancy and pass one another centrally, the eclipses will be equal and the loss of light one-half. And it is noteworthy that in nature this seems to be a somewhat prevalent arrangement. Several systems are known in which it may subsist; spectroscopic observations can peremptorily decide whether it does, in fact, subsist or not. The principle of their decision lies on the surface. Eclipses necessarily take place at points of the orbit where radial motion approximates to zero. If they are duplicated in each period, the cessation of movement marks at one, the transition from speed of approach to speed of recession; at the next, the turning-point where speed of recession changes to speed of approach. A minimum of light, that is to say, precedes each reversal of movement. If, on the other hand, the eclipses are single, occurring only once in a revolution, the cycle of motion to and from the eye is completed in the interval between them. The criterion is thus absolute and unmistakable; only the faintness of the stars impedes its general application. Where unequal eclipses alternate, however, the spectroscope is not needed to inform us that they take place two and two in each circuit. They are then evidently due to the mutual occultations of disparate stars; and the species of combination they indicate is frequently met with. It is varied to the utmost, as might be expected, by gradations of disparity, in the production of which deficient luminosity may concur with inferiority of size, or be partially neutralised by its superiority. Thus as

each globe in its turn comes in front of the other, there results a double series of eclipses, the odd ones (dating from a fixed epoch) being perfectly similar each to each, but differing in depth and duration from those of the even or intermediate series.

Further diversities arise through slight tilting of the orbits. The corresponding eclipses are partial, even to the limit of evanescence, when the star discs just escape contact. And it may be noted that the second eclipse in each revolution, properly belonging to a luminous pair, may be suppressed where the path traversed is at the same time sensibly inclined and considerably eccentric. Partial eclipses are doubtless the rule, central ones the exception; but their discrimination is often a matter of some delicacy. Indeed, the photometric study of such phases is an art in itself, the practice of which demands skill, vigilance, and patience beyond the common. The aid of photography, lately enlisted for it, is likely to enhance its security and precision.

Eclipsing stars, once more, are close binaries circulating nearly in the line of sight. Not any intrinsic peculiarity, but our situation in space, determines their special character. Relatively to us, they are periodically variable, as Spica or Castor would become were our place suitably shifted. Their changes are of a distinctive kind; they are short, sharp, and decisive. When well developed, that is to say; for photographic photometry may ere long afford the means of detecting occultations barely adumbrated by a drop not perhaps exceeding one-tenth of a magnitude. All members of the class so far have been recognised by their variation in brightness; their accompanying circulatory motion, inferred in all cases, has been verified in only a few. The following list gives the designations, periods, and phases of the eclipsing stars with which astronomers had made acquaintance down to the end of 1902. They are enumerated in the order of their discovery.

[TABLE.

| Chandler's No. | Name. | Period. | Light Range. | Duration of Phase. |
|---|---|---|---|---|
| | | d. h. m. s. | m. m. | h. m. |
| 1090 | Algol | 2 20 48 55 | 2·3 to 3·4 | 9 20 |
| 3109 | S Cancri | 9 11 37 45 | 8·2 „ 9·8 | 21 30 |
| 1411 | λ Tauri | 3 22 52 12 | 3·4 „ 4·2 | 10 0 |
| 5374 | δ Libræ | 2 7 51 23 | 5·0 „ 6·2 | 12 0 |
| 5484 | U Coronæ | 3 10 51 12 | 7·5 „ 8·9 | 9 42 |
| 6546 | RS Sagittarii | 2 9 58 36 | 6·4 „ 7·6 | 10 40 |
| 320 | U Cephei | 2 11 49 38 | 7·1 „ 9·4 | 11 0 |
| 6189 | U Ophiuchi | 0 20 7 43 | 6·0 „ 6·7 | 5 20 |
| 7488 | Y Cygni | 1 11 57 26 | 7·1 „ 7·9 | 9 0 |
| 2610 | R Canis Majoris | 1 3 15 46 | 5·9 „ 6·7 | 5 0 |
| 5949 | R Aræ | 4 10 12 42 | 6·9 „ 8·0 | 9 30 |
| 3055 | X Carinæ | 0 12 59 30 | 7·9 „ 8·6 | 6 39 |
| 5144 | Y Bootis | 2 14 24 0 | 8·0 „ 8·6 | 4 0 |
| 3416 | S Velorum | 5 22 24 35 | 7·8 „ 9·3 | 15 11 |
| 6442 | Z Herculis | 3 23 50 0 | 6·9 „ 8·0 | 6 36 |
| 7399 | W Delphini | 4 19 21 12 | 9·3 „ 12·1 | 14 0 |
| 6636 a | RX Herculis | 0 21 20 33 | 7·0 „ 7·8 | 4 8 |
| 2781 | R² Puppis | 6 10 19 36 | 9·1 „ 10·8 | 17 0 |
| | U³ Cygni | 4 13 45 2 | 8·7 „ 11·4 | 13 0 |
| | V² Cygni | 6 0 8 48 | 10·8 „ 12·8 | ... |
| 3707 | R² Velorum | 1 20 30 2 | 10·0 „ 10·9 | 3 20 |
| 6773 | U Scuti | 0 22 54 0 | 9·1 „ 9·6 | 5 0 |
| 7318 | UW Cygni | 3 10 49 12 | 10·5 „ 12·0 | 8 30 |
| 6927 | U Sagittæ | 3 9 19 12 | 6·5 „ 9·1 | 12 0 |
| 7891 | UZ Cygni | 31 7 17 46 | 8·9 „ 11·85 | 48 0 |
| | RV Lyræ | 3 14 22 23 | 11·0 „ 12·8 | ... |
| | 14, 1902 Persei | 3 1 21 32 | 9·4 „ 12·0 | ... |

Algol (β Persei) is the model eclipsing star. Goodricke's sagacious conjecture that such was its nature, adopted and developed by Pickering, obtained experimental confirmation after a lapse of 107 years. Vogel's spectrographs showed in 1889 that, previously to each obscuration, the star was swiftly receding from the earth, while recovered brightness was attended by a somewhat greater velocity of approach. The excess is simply due to the fact that the system is travelling towards the sun at the leisurely pace of $2\frac{1}{3}$ miles a second. The true orbital speed is sensibly uniform; accelerations, pointing to ellipticity in the track pursued, have not been detected. One eclipse takes place in each revolution; the eclipsing body is to all intents and purposes a gigantic planet; it gives no perceptible light. The sun round which it circulates is, on the contrary, peculiarly brilliant for its size, partly because its absorption, being of the helium type, produces little or no mellowing effect upon its keen white rays.

Much has been learned about the system formed by these contrasted globes. Its visible member travels at the rate of 26⅓ miles a second; and since the period of revolution comprises 247,735 seconds, the distance of its centre from the centre of gravity slightly exceeds 1,000,000 miles. The length of the eclipse, moreover, gives the actual size of the star. It has a diameter of slightly more than 1,000,000 miles, or about five-fourths that of the sun. The dimensions of the satellite, too, are approximately known. From the loss of light through its interposition, Professor Pickering in 1880[1] calculated the ratio of its diameter to that of its primary to be as 764 to 1000. The ratio should be increased if the transit were not central, which it does not appear to be. For the eclipse is not annular, since there is no pause at minimum; the flow of change is continuous; the turning of the luminous tide is not appreciably delayed; decline is immediately succeeded by restoration. The orbit is not then level with the eye; and Mr. Yendell considers that an inclination of 7° would agree best with the light-curve.[2] In Vogel's opinion it is such as to imply for the dark body a diameter of 830,000 miles, an estimate which can hardly be far from the truth.[3] Admitting with him that the two stars are of equal density—possibly a hazardous assumption—we can infer their masses, knowing their respective volumes, and the circulatory speed of one of them. They are in the proportion of two to one, and both spheres together contain two-thirds as much matter as our sun. They are, accordingly, at least four times more tenuous; but the consequence cannot be said to discredit the postulate in view of the extreme rarefaction characterising white stars in general and helium stars in particular. The distance of Algol from its satellite (always on Vogel's hypothesis of equal densities) is 3,230,000 miles, leaving an interval between their surfaces of scarcely more than 2,250,000 miles. But we shall find that even closer degrees of contiguity are compatible with stability in the mechanism of the stellar heavens.

The period of Algol has long been known to vary

[1] *Proc. Amer. Academy*, vol. xvi. p. 27.

[2] *Popular Astronomy*, Oct. 1897, p. 306.

[3] *Sitzungsberichte*, Berlin, 28th Nov. 1889; *Astr. Nach.* Nos. 2947, 2960.

minutely but continuously. But as to the nature, law, or cause of these inequalities nothing had been ascertained, and little had even been surmised, prior to Dr. Chandler's discussion of them in 1888.[1] He proved them to be slowly compensatory, not indefinitely progressive. Consistently in advance of their due time down to about the year 1804, the obscurations of the star then began to fall behind it, and the delay had in 1843 accumulated to 156 minutes. A gradual process of restoration thereupon set in, and the normal epoch was reached near the beginning of 1873. It was, however, quickly transcended, for acceleration was still going forward, and may not attain its term for some years yet to come.[2] These irregularities are evidently comprised in a cycle of considerably more than a century; they can scarcely, for that very reason, be accounted for on gravitational principles; since a third body, revolving in so long a period, would be too distant to perturb markedly the movements of the close pair traversing an inner circuit. Dr. Chandler hence resorted to another mode of explanation.[3] He proposed to account for the alternate anticipations and retardations of Algol's eclipses on the principle of the equation of light. They might result, he pointed out, from the description, by the occulting pair, of an orbit so wide that the transmission of light across it takes close upon 300 minutes. The star's phases would then be observed too soon or too late according as they occurred on the hither or the farther side of the great ellipse. They would be shifted by turns backward and forward in time just as are the eclipses of Jupiter's satellites while the earth performs its annual circuits. The system of Algol is, on this view, triple. Two dark masses and a vividly shining one unite to form it. The revolutions of the eclipsing pair round the common centre of gravity, which is at a distance from it just equal to that of Uranus from the sun, are accomplished in about 130 years, at the rate of 2·7 miles a second. Its members are at present nearer to us than their mean place, and their occultations consequently forerun the mean times; this will continue until towards the year 1934, when,

[1] *Astr. Journ.* vol. vii. p. 165.
[2] *Knowledge*, vol. xv. p. 86 (A. M. Clerke).
[3] *Astr. Journ.* Nos. 255, 256, 257.

on the passage of the ascending node, a coincidence of epochs should be observed. Two other criteria are applicable to Chandler's theory. If it be true, Algol's approaching systemic movement of 2·3 miles a second should disappear within the next decade, neutralised by orbital velocity at that time directed away from the sun. Again, the wide circuits performed in a plane supposed to make an angle of 20° with the line of sight, might be directly traceable as undulations impressed upon the straight track of the star's proper motion. Minute fluctuations of position simulating the looked-for effects have indeed been observed; but whether they are merely casual, or represent an actual, though almost evanescent phenomenon, is too delicate a question to be decided offhand.[1] Twenty years hence the waves of disturbance may have defined themselves;[2] scarcely sooner.

An alternative hypothesis to Chandler's was put forward by M. Tisserand early in 1895.[3] Rejected by the former investigator as insufficient, it assumed in the hands of the latter an extremely plausible form. No third body is demanded by it; a slight flattening of the globe of Algol, together with a moderate degree of ellipticity in the orbit of its satellite, meet the needs of explanation. The combined effect would be to produce a slow revolution of the orbital major axis, occasioning just such an inequality in the times of conjunction as that discussed by Dr. Chandler; and the fundamental postulated cause is likely to be present. Algol must have a rapid rotation; otherwise its system could not long subsist. That is to say, the maximum length of its axial period is $2^d\ 21^h$, the period of its revolution. This implies an equatorial speed of $13\frac{1}{2}$ miles a second, and a consequent equatorial bulging of very considerable amount. One of the conditions stipulated by Tisserand may then be granted, and the second can scarcely be absent, since the eccentricity of stellar orbits rarely falls short of the degree required. Verification may be procured by the spectroscopic detection of variations of velocity in different sections of Algol's

[1] Bauschinger, *V. J. S. Astr. Ges.*, Jahrgang xxix.; Chase, *Astr. Journ.* No. 218.

[2] Boss, *Astr. Journ.* No. 343; Yendell, *Pop. Astr.* Dec. 1897, p. 401.

[3] *Comptes Rendus*, t. cxx. p. 125; *Bull. Soc. Astr. de France*, 1895, p. 73.

path. But the crucial test of the theory is of the photometric kind. At intervals of 120 years, if it correspond with fact, the shortest and longest radii of the ellipse traversed would, owing to the progression of the apsides, alternately point towards the earth. In the first case, the eclipses would be abbreviated by periastral acceleration; in the second, they would be long, because the movement at apastron should be slow. Their duration at present approaches to being the longest possible; if they shorten notably from 1910 onward, Tisserand's hypothesis will be amply confirmed, while their failure to do so will compel its final rejection. Chandler's, on the other hand, will remain in possession of the field should the alleged periodical disturbance of Algol's proper motion be definitively established. Thus the rival theories alike wait on the future, and invite the award of events.

As the upshot of a careful series of measurements with the Yale heliometer, Dr. Chase [1] ascribes to Algol a parallax of 0·035″, equivalent to a light-journey of ninety-three years. If actually so remote, it gives just eighty times as much light as the sun from a surface not very greatly larger, but fifty-two times more brilliant—an inference surprising indeed, but not incredible.

A second Algol-variable was recognised by Hind in 1848.[2] Usually of 8·2 magnitude, S Cancri loses and regains more than three-fourths of its light in 21½ hours, divided between 8½ of decline and thirteen of restoration. The dissymmetry of the phases is increased by a remarkable pause in the brightening after minimum, as if a secondary cause of obscuration had supervened. Nor should it be forgotten that Schmidt observed on 14th April 1882 an excessive darkening of the star, which remained for a whole hour sunk nearly to the twelfth magnitude. The period which, until lately, was the longest ascertained for any member of its class, is subject to a cyclical disturbance embracing at least 300 light-cycles.[3] The deviations of the computed minima sometimes run up to forty minutes. It will be of great interest to determine whether they imply the presence of a third attractive body, or

[1] *Astr. Journ.* No. 318.

[2] *Astr. Nach.* No. 804.

[3] Schönfeld, *V. J. S. Astr. Ges.*, Jahrgang ix. p. 230; *Sirius*, Bd. x. p. 68; Argelander, *Bonner Beob.* Bd. vii. p. 397.

whether spheroidal deformation will suffice to account for them. The dimness of S Cancri places it for the present beyond the reach of useful spectrographic research. Its density has, however, been calculated by Mr. H. N. Russell of Princeton University,[1] from the ratio between its period of revolution and the duration of the eclipses suffered by it, with the result of showing that the star is composed of materials forty times more attenuated than those of the sun! And this is an upper limit.

Shortly after Hind's detection of S Cancri, Baxendell found that its peculiarities were shared by λ Tauri, a radiantly white star of 3·4 magnitude. Its eclipses, as in several other cases, deepen more quickly than they lighten. They occur at intervals of $3^{d}$ $23^{h}$, and last ten hours. They do not, indeed, come off quite punctually. An oscillatory disturbance of unknown law affects them, which occasions "errors" from the computed epochs, amounting at times to three hours.[2] Plassmann regards λ Tauri as continuously variable.[3] He noticed in 1891 a secondary dip in brightness fifty hours after the chief minimum, besides two intermediate maxima; and the Pulkowa photographs lent in 1897[4] some partial countenance to his views. They showed the spectrum to be occasionally and unequally double, the fainter rays, by their relatively large displacements, betraying their origin from a mass greatly inferior to that of the star characterised by the less mobile, and more intense absorption-lines they accompany. Thus M. Plassmann's second eclipse[5] is real, though inconspicuous. No orbital elements have yet been assigned to this star. M. Bélopolsky regarded his materials as inadequate for purposes of computation; and indeed the movements derived from his plates were of a somewhat problematic nature. They greatly need elucidation, which it ought not to be very difficult to supply. The spectrum of λ Tauri is of pure helium type. The calculated density of the pair is about one-tenth that of the sun.

The fourth Algol variable is an all but perfect timekeeper. The phases of δ Libræ have been watched since 1858 without

[1] *Astroph. Journ.* vol. x. p. 317.

[2] Schönfeld, *Jahresbericht*, Mannheim, Bd. xl. p. 76.

[3] *Beobachtungen Veränderlicher Sterne*, Th. iii. p. 21.

[4] *Astr. Nach.* No. 3474.

[5] *Journ. Brit. Astr. Assoc.* vol. i. pp. 187, 255.

the detection of any assured irregularity. They last twelve hours, of which 5½ are spent in a decline from 5·0 to 6·2 magnitude, and 6½ in the reversal of the process. The eclipsing body appears to be wholly obscure, but the spectrographic method has not been applied to the system. The limit of density found for it by Mr. H. N. Russell is one-twenty-fifth that of the sun.

The phases of U Coronæ are very similar to those of Algol, but the intervening time is longer—eighty-three in lieu of sixty-nine hours. Each pair, too, is similarly composed of a bright and dark member, and their mean density comes out nearly the same. The analogy is completed by the presence of a variation in the period, evidently akin to the disturbances of Algol,[1] and explicable, doubtless, on an identical principle. U Coronæ, however, is a comparatively faint object; at high light it is of only 7·5 magnitude, and consequently offers scant facilities for research.

The eclipsing system designated RS Sagittarii, discovered by Gould in 1874, was subjected in 1896 to exact inquiries by Alexander W. Roberts of Lovedale, South Africa.[2] From them it appears that the coupled stars are alike in size, but so unlike in lustre that one gives more than twice as much light as the other. There result two unequal minima in each revolution; at the first, the combined magnitude of 6·6 drops to 7·6, at the second, to 6·9. The former has, besides, a duration of $10^h\ 40^m$, the latter of only seven hours; whence the orbit is found to have an eccentricity of 0·25, the long, deep eclipse occurring at apastron, the slighter phase coinciding with the rapid sweep through periastron. The intervals of time from each to the next are of $2^d\ 10^h$ very nearly; and their equality implies that the major axis of the path pursued is directed towards the earth. The plane of the ellipse, however, must be somewhat inclined, since the mutual transits of the globes circulating in it are not central; and the amount of its inclination may be determined when the course of light-change is more accurately known. The gravitational period (as it may be called) is, of course, double the eclipse-period, or $4^d\ 20^h$; but the mass of the system can

[1] Chandler, *Astr. Journ.* No. 205.

[2] *Astr. Journ.* No. 373; *Astroph. Journ.* vol. iv. p. 267.

be ascertained only by spectroscopic means. Its brighter member proves to be of about one-sixth, the dim component of one-fifth, the solar density.[1] All these particulars have been gathered from the photometric relations of these intimately conjoined bodies. From their dynamical relations, truths no less remarkable will perhaps before long be elicited.

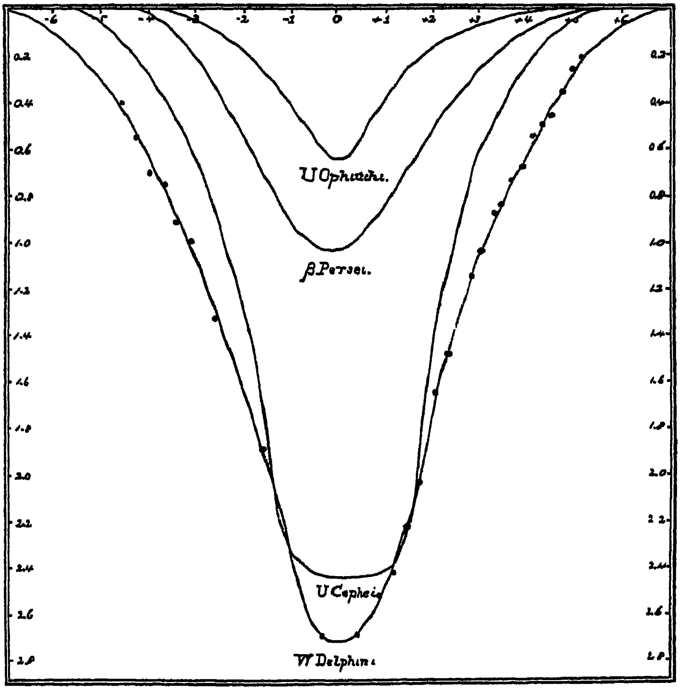



FIG. 21.—Photometric Curves of Algol Variables (Pickering).

At Moscow, in 1880, U Cephei was added by Ceraski to the Algol family. This object is distinguished by the abruptness and extent of its changes. In four and a half hours it descends from 7·1 to 9·4 magnitude, this profound obscuration lasting for about two hours, after which brightness returns, almost, if not quite as quickly as it departed. The light-curve, determined photometrically by Professor Pickering, is shown in Fig. 21.

[1] Roberts, *Astroph. Journ.* vol. x. p. 313.

He explains its singularities on the hypothesis of a total eclipse by a large semi-obscure body,[1] and alleges confirmatory evidence in a barely perceptible secondary minimum corresponding to the transit of the brilliant over the dusky globe. Chandler and Yendell, nevertheless, deny the reality of the minor eclipse;[2] and Wilsing vainly endeavoured in 1890[3] to bring the observed phases of U Cephei into harmony with any conceivable form of the occultation-theory. And the star, by its faintness, evades spectrographic tests for motion. Some increase of blue absorption is, however, stated to occur at its minima; and this is noteworthy as an instance, unique among Algol variables, of alteration in the quality of their diminished rays. Irregularities of the same type as those of Algol affect the period of U Cephei. If dependent on the light-equation principle, they signify the description, by the eclipsing couple, of an orbit larger than the Saturnian, in a period of between thirty and forty years.[4] Changes in radial motion, due to deflection in this wide path, would, if measurable, lend authenticity to an ingenious speculation, which may otherwise be superseded by Tisserand's hypothesis[5] of a revolving major axis. Mr. Russell finds U Cephei to be a considerably more tenuous body than Algol.

The exceedingly short period of U Ophiuchi—$20^h\ 8^m$—and the halving of its light at minimum, suggest that it is composed of twin suns, alternately occulting one another. The period of revolution would, in that case, be twice the period of variation, and the globes would have more room to circulate than if one of them were dark. For then the brief intervals between the eclipses would represent each a complete round of the orbit, and the duration of the phases would imply such close proximity of the bright and the dark stars that the gap dividing their surfaces would scarcely exceed three-tenths of their joint radii. Such an arrangement is possible; a single spectrographic impression, taken five hours before or after a minimum, would show whether it actually subsists. If it do,

[1] *Proc. Amer. Acad.* vol. xvi. p. 350; *Astr. Nach.* No. 3385.
[2] *Astr. Journ.* No. 199; *Popular Astr.* Sept. 1897, p. 239.
[3] *V. J. S. Astr. Ges.* Jahrgang xxvi. Th. ii.; *Potsdam Annual Report.*
[4] Chandler, *Astr. Journ.* Nos. 199, 294, 396.
[5] Tisserand, *Bull. de la Soc. Astr. de France*, Mars 1895.

the spectral lines will be single, though shifted; if not, they should appear incipiently double, and the movements indicated might unhesitatingly be taken to be included in a cycle twice the length of the eclipse-interval.

Discovered by Sawyer in 1881, U Ophiuchi showed to Chandler's patient scrutiny individualities that should not be passed over.[1] Thus the return of light after minimum is interrupted by a pause similar to that observed in S Cancri, but which tends to become obliterated in a "mean curve." Its reality has not been established photometrically (see Fig. 21), but may emerge with the application of finer methods. The circumstance, too, is worth remark that—again like S Cancri—U Ophiuchi was once caught sight of during an abnormally obscure phase.[2] An inequality of its period, comprised within thirty-seven to forty years, further noticed by Chandler, is perhaps visibly reflected in the disturbance of the star's proper motion.

A still more curiously interesting object of the same class is met with in Y Cygni. Here, at least, as M. Dunér virtually demonstrated in 1892,[3] eclipses are duplicated; two occur in the course of each revolution. Its phases, first recognised by Chandler, 9th December 1886, range from 7·1 to 7·9 magnitude, and are completed in nine hours. But they were soon perceived to recur with conspicuous irregularity.[4] Towards the middle of 1888 they were no less than seven hours behind their calculated times, which shortly afterwards began to be largely anticipated. Perturbations on such a scale had never previously been betrayed by the occultations of a binary; and the task of accounting for them by inequalities of light-transmission was evidently a formidable one. The problem they offer was, however, destined to receive a different, and, we may add, a definitive solution.

When Dunér came to discuss the results of his own observations at Upsala in 1891-92, and to compare them with those made elsewhere, he was at once struck with a persistent

[1] *Astr. Journ.* Nos. 162, 294.

[2] *System of the Stars*, p. 142.

[3] *Astr. Nach.* Nos. 3091, 3467; *Astr. Journ.* No. 265; *Trans. Swedish Acad. of Sciences*, 1892, No. 7.

[4] Yendell, *Astr. Journ.* Nos. 163, 185; *Knowledge*, vol. xvi. p. 166 (A. M. Clerke).

discrepancy between the odd and the even sets of minima. The first, third, fifth, and so on, from an assigned epoch, obeyed a law of recurrence quite distinct from that conformed to by the intervening obscurations. Thus in November 1891, the intervals from an even to an odd minimum, and from an odd to an even minimum, differed by no less than nine hours, forty-three minutes. Clearly, the constant sum of these discrepant periods gives the true time-measure of systemic circulation. Two bright bodies, then, eclipse each other, and they seem to be matched "to a hair"; their eclipses, moreover, must be central, since the loss of light amounts to just one-half. The disparity of their intervals depends primarily upon the eccentricity of the orbit; secondarily, upon the situation of the line of apsides. It vanishes when the line in question points directly towards the earth; it attains a maximum when it is viewed at right angles, for then the right and left sections of the eclipse being traversed respectively with the least and greatest possible velocities, the succession of alternate occultations reaches the limit of time-inequality. Dunér's final conclusions regarding the system were expressed as follows:—[1]

"The variable star Y Cygni consists of two stars of equal size and equal brightness, which move about their common centre of gravity in an elliptical orbit whose major axis is eight times the radius of the stars. The period of an anomalistic revolution[2] is 2·996933 days, and the eccentricity is 0·145. A minimum occurred while the stars were at periastron, on 8th December 1885. The line of apsides of the orbit, which then coincided with the line of sight, completes one revolution in the plane of the orbit in 41·1 tropical years."

The next coincidence of the kind, if the above elements are correct, should take place in 1906. The compelling cause of the orbit's gyration remains to be investigated. It may be found in disturbance exercised by an unseen, exteriorly revolving mass upon the conjoined suns; or their own spheroidal shape may be solely concerned in producing it; the question has an important bearing upon the construction of all such systems. The linear dimensions of the orbit of Y Cygni will

[1] *Astroph. Journ.* vol. xi. p. 190.

[2] *I.e.* the interval between one perihelion passage and the next.

unquestionably be determined ere long with the spectroscope, whence the mass of the bodies travelling in it will at once follow. A mean density less than one-sixth the solar is ascribed to them with some confidence.[1]

The variations of R Canis Majoris, detected by Sawyer in 1887, have been traced, as it were, only in outline. Their period is $28^h\ 16^m$, five hours of which are occupied by the phases, and since the star fades to half its normal lustre, they are likely to be conditioned much as are those of Y Cygni. Two similar globes presumably undergo them in turn, mutually revolving in double the period of their occultations.

The character of R Aræ was noticed by Mr. A. W. Roberts in 1891.[2] He considers the eclipses, which recur once in $4^d\ 10^h$, to be not always of the same depth; but this symptom of intrinsic variability in one or both of the transiting stars needs to be verified. The curve at minimum is symmetrical.

The nature of X Carinæ—another southern variable discovered by Roberts in 1892—is still dubious. It changes from 7·9 to 8·6 magnitude in $6^h\ 39^m$, and remains constant only during $6^h\ 20^m$. So that the phases extend over more than half the period of variation, which must evidently be doubled to give the period of revolution, since no eclipse can possibly have a duration of more than one-half the occulted body's orbital circuit. The alternate minima of X Carinæ are thought by Roberts[3] to be, to a very small extent, unequal, and to succeed each other at slightly different intervals. If this be so, the system is composed of two stars, one a little brighter than the other, pursuing a nearly circular track in a period of twenty-six hours, and in such close contiguity that the times during which their discs overlap are longer than the intervals of their apparent separation. The actual subsistence, however, of this, or some analogous arrangement has yet to be proved.

The variations of Y Bootis are also more or less enigmatical.[4] They are limited to six-tenths of a magnitude, and have a period rather shorter than that of Algol. The eclipsing character of this eighth-magnitude star, suggested by Park-

[1] Russell, *Astroph. Journ.* vol. x. p. 318.
[2] *Astr. Journ.* Nos. 327, 383.
[3] *Ibid.* No. 383 ; *Astroph. Journ.* vol. iv. p. 272.
[4] Chandler, "Third Catalogue of Variable Stars," *Astr. Journ.* No. 379.

hurst in 1893,[1] was confirmed, on the strength of a year's observations, by Yendell. Chandler, nevertheless, expresses doubts as to its genuineness, which is compromised by extraordinary anomalies, hardly amenable to explanatory efforts. The predicted minima do not always occur, and their failures seem capricious and inconsequential. But if they depended, as Parkhurst thinks they must,[2] upon a certain critical inclination of the orbit, causing transits to be occasionally missed, a law of periodicity should be traceable in the lapsed phenomena.

The obscurations of S Velorum recorded themselves on the plates of the Cape "Durchmusterung," and the record was duly interpreted by Mr. Ray Woods in 1894.[3] They are marked by the same peculiarities as those of U Cephei, and probably indicate total effacements of a radiant sun by the prolonged transits across it of a voluminous, but dimly shining companion sphere, the diameter of which, according to Roberts,[4] cannot fall short of half the distance between the revolving bodies. Their respective densities, as estimated by him, are 0·61 and 0·03 that of the sun,[5] the dusky mass proving, on the assumed data, to be twenty times more rarefied than the brilliant one. A disparity so extreme cannot readily be admitted as real. If only the star could be elevated on the photometric scale,[6] the taking of a few spectrographs would at once acquaint us with the true plan of its system; but its faintness—7·8 magnitude—must long continue to baffle experiments of this kind.

A modified specimen of the Y Cygni sub-class is met with in Z Herculis. Its eclipsing character was announced by Chandler in 1894;[7] about a month later, Hartwig and Dunér independently detected in it a double sequence of disparate minima, with periods respectively of forty-seven and forty-nine hours. Hence the revolution of a pair of unequally bright stars in a period of just four days was inferred with virtual certainty.[8] In M. Dunér's words, "Z Herculis consists of

[1] *Astr. Journ.* No. 326. [2] *Ibid.* Nos. 329, 384, 415.
[3] *Monthly Notices*, vol. lv. p. 211.
[4] *Astr. Journ.* No. 327; *Astroph. Journ.* vol. iv. p. 270.
[5] *Ibid.* vol. x. p. 314. [6] Keeler, *ibid.* vol. i. p. 262.
[7] *Astr. Journ.* No. 328.
[8] *Astroph. Journ.* vols. i. p. 294; iii. p. 348; *Astr. Journ.* Nos. 374, 384, 422.

two stars of equal size, one of which is twice as bright as the other. These stars revolve round their common centre of gravity in an elliptical orbit, the semi-axis major of which is six times the diameter of the stars. The plane of the orbit passes through the sun, the eccentricity is 0·2475, and the line of apsides is inclined at an angle of 4° to the line of sight." The chief minimum lasts 6·6 hours, and occurs not far from apastron. The secondary phase is hurried through in four hours, when the stars are moving with nearly their greatest speed. It is, however, unlikely that this relation will continue unchanged;[1] since it may be taken almost as an axiom that orbits so conditioned pivot round in space, turning their longest axes successively in every direction.

The first Algol variable photographically discovered was W Delphini. On 18th July 1895, Miss Louisa D. Wells missed a 9·3 magnitude star from a Harvard plate exposed 26th September 1891,[2] while upon seventy-one earlier and subsequent ones it was normally imprinted. The one tell-tale photograph had been taken during eclipse, when it sinks to 12·1 magnitude—that is to say, eleven-twelfths of its light are cut off by the interposing body. Pickering[3] believes the latter to be partially luminous and very large, affording prolonged totalities, but the photometric curve (see Figure 21) hardly warrants this assumption. It is fairly sharp at minimum, not flat, like that of U Cephei, and corresponds better with a partial occultation by a wholly dark satellite than with the central transit of one dimly radiative. The period is not constant.[4] Deviations from regularity amounting to one hour had become manifest early in 1898.

The phases of a seventh-magnitude star (DM + 12° 3557) named RX Herculis were discovered by Sawyer in 1898.[5] They range over eight-tenths of a magnitude, and recur at intervals of $21^h$ $21^m$. Like those of U Ophiuchi, they probably indicate the revolution, in double that period, of two equal stars; and since the minimum brightness is just one-half the maximum, their mutual occultations may be total.

1 Yendell, *ibid.* No. 366.

2 *Harvard Circulars*, Nos. 3, 4.

3 *Astroph. Journ.* vol. iii. p. 213.

4 Pickering, *ibid.* vol. vii. p. 23.

5 *Astr. Journ.* Nos. 447, 450; Luizet, *Astr. Nach.* No. 3596.

The variability of $R^2$ Puppis (CPD − 41° 1681), noticed by Professor Kapteyn during his inspection of the Cape Durchmusterung negatives, was verified and defined by Mr. Innes in 1899.[1] The period at first assigned of nearly thirteen days was abridged to one-half that length by Mr. Roberts's investigations.[2] The light fades at minimum to one-third its full amount, through the intervention of a dimly luminous mass.

$U^8$ Cygni and $V^2$ Cygni were both detected by Madame Ceraski in studying photographs of the sky taken at Moscow.[3] They undergo analogous changes, investigated at Harvard College in 1899-1900.[4] Those of $U^8$ Cygni are remarkable for their extent, the greatest known in an eclipsing star, unless (which is doubtful) W Delphini should be bracketed with it. $V^2$ Cygni, at full brightness, ranks little higher than the eleventh magnitude, and descends, once in six days, nearly to the thirteenth. It is thus an object at the limit of detailed observation. Innumerable systems of the same kind must lie beyond that limit. The twenty-first star on our list—$R^2$ Velorum—suspected as an Algol variable by Innes in 1901, was verified and investigated by Roberts.[5] Of the remaining six objects enumerated, U Sagittæ was found by M. Schwab of Ilmenau to vary after the manner of U Cephei;[6] and UZ Cygni, detected by Mrs. Fleming in 1902, is remarkable for a period more than thrice as long as that of S Cancri. UW Cygni, RV Lyræ, and the still unnamed star in Perseus have been recently discovered by Mr. Stanley Williams.

Algol variables, without any recognised exception, show first-type spectra. They are either helium or Sirian stars. This specialty is unaccountable, and may perhaps vanish with the widening of experience; for many close binaries exempt from eclipses belong to the solar class, and no reason is apparent why those happening to revolve in planes coincident with the visual ray should differ in quality of light from those revolving in orbits variously inclined to it. Nor is it yet

[1] *Astr. Journ.* No. 468. [2] *Astroph. Journ.* vol. xiii. p. 177.
[3] *Astr. Nach.* Nos. 3572, 3567; Parkhurst, *Astr. Journ.* No. 475.
[4] *Harvard Circulars*, Nos. 44, 47.
[5] *Astr. Journ.* No. 508; *Proc. Royal Society of Edinburgh*, 4th Nov. 1901.
[6] *Astr. Nach.* Nos. 3748, 3765; *Astr. Journ.* No. 517.

quite certain that the eclipse-theory accounts for certain minor phenomena in the stars to which it applies. Thus some of their light-curves, as drawn visually, are marked by peculiarities incapable of being explained as the outcome of purely dynamical relations. They may, however, turn out to be illusory or subjective; their reality is not incontrovertible. Again, the exceptionally low minima recorded for S Cancri and U Ophiuchi need confirmation. The possibility of mistake is not excluded so long as each remains an isolated event.

Three varieties of eclipsing stars may be distinguished. The first includes bright and dark pairs, like Algol and its companion, revolving in slightly oblique orbits. One partial occultation takes place in each revolution. The intimate association which they present of bodies at opposite extremes of luminosity is not a little remarkable. In the second variety, exemplified by U Cephei, a brilliant star circulates round a larger, but far less lustrous globe. One prolonged totality marks the orbital period. The secondary minima, theoretically inevitable in such cases, have not been certainly observed. Vanishing stars, could they be discovered, would appropriately illustrate this mode of construction where the contrast in light-power had reached its limit. Finally, the third species of occulting systems consists of stars undergoing nearly equal double eclipses, the period of revolution comprising two periods of variation. Y Cygni is a typical example. If the loss of light amount to one-half, or eight-tenths of a magnitude, and the alternate minima be of the same intensity, the eclipses are total; for two similar stars, one is temporarily substituted. If, owing to the inclination of their path, they only partially conceal one another, the phases will be slighter, yet still equal. Their disparity, in odd and even series, shows at once that the balance of luminosity is tilted; and indications are not wanting that its level is disturbed rather by inequalities of intrinsic lustre than of shining area.

The time-keeping of eclipse-stars is a subject demanding profound and persistent study. The minutest irregularities traceable in it may be of far-reaching significance.[1] On what principle they should be explained, is still largely an open

[1] Such have recently been detected by Chandler in Algol, *Astr. Journ.* Nos. 509, 511.

question. Possibly several forms of action conspire, even in the same system, to produce the sum-total of their deviations. In no case has the presence of a third body been proved; in no case have perturbations of the ordinary gravitational type been suspected. On the other hand, the occulting and the occulted globes must be deformed through rotation; hence one *true* cause for the observed inequalities falls within our ken; whether it is a *sufficient* cause alone remains doubtful. Essentially, however, increase of knowledge regarding these marvellous combinations depends upon the development of spectrographic methods. Surely, although perhaps in slow succession, they will yield the secrets of their construction to a mode of inquiry that continually gains power and accuracy, and is capable of dealing directly with the most recondite springs of celestial mechanics.

# CHAPTER XIX.

## SHORT-PERIOD VARIABLES.

THE limit of length for "short periods" of stellar variation is conventionally fixed at thirty days; but it is seldom reached by objects of typical character. Rapid fluctuations are almost always accomplished with extreme exactitude both as to time and amount. To this rule there are very few exceptions, and a reason for it is not difficult to find. Variability of the kind in question is precise because it originates extrinsically. It might be called a "forced vibration" of change. Its course is, in some way, prescribed by the revolutions of a satellite. No more curious spectroscopic discovery has been made than that of the binary nature of short-period variables. By it a breach has been made in the wall of mystery surrounding stellar light-change. The breach has not yet been mounted, nor is it quite practicable; but by persevering efforts it can be gradually widened and levelled.

In dealing with variable stars we must proceed tentatively. The subject is so complex that no intelligible view of it can be gained all at once. A unifying principle is still lacking. We can only take things as they present themselves, noting differences, tracing partial analogies, and arranging into some fashion of order a multitude of heterogeneous examples. Thus stars fluctuating in short periods may be separated into three families. The first has $\delta$ Cephei, the second $\zeta$ Geminorum for its head, and their members may conveniently be designated Cepheid and Geminid variables. The third is represented profusely, but almost exclusively, in globular clusters. To begin with the Cepheids.

They are numerous and well known. Their changes are

continuous and of moderate amplitude, but proceed unsymmetrically as regards time. The rise to maximum occupies on an average about a third of the period, or half the time allowed for the decline from it to minimum. This retardation is accompanied by an inherent tendency to a second maximum, sometimes barely indicated as a pause in descent, but in several cases giving rise to a pronounced "hump" on the downward slope of the light-curve. The variations of δ Cephei range from 3·7 to 4·9 magnitude in $5^d\ 8^h\ 47^m\ 39^s$, of which $1^d\ 14^h\ 36^m$ suffice for the phases of increase. The spectrum is of the solar type, and does not change with the brightness. Oscillatory movements, however, of its constituent lines, detected by Bélopolsky in 1894,[1] betray the presence of an obscure companion revolving in the light-period. The ellipse described is so eccentric that the companion-bodies when at apastron are three times further apart than at their nearest approach; and its major axis deviates only by two degrees from a vertical plane passing through the earth. There is nothing indeed to show that it may not be highly inclined to the corresponding horizontal plane. The orbital level is undetermined, being evidently such as to exclude eclipses. This was unexpected, but it is certain. The criterion is simple. Radial velocity should vanish at minima if a transiting globe were concerned in their production; in point of fact, the epochs of least brightness precede the epochs of conjunction by a full day. The system of δ Cephei is not then an eclipsing system. The star's variability must be otherwise accounted for. Nor would it be easy, without abusing the licence of hypothesis, to expound it as the result of occultations. The inducement to make the attempt is, at any rate, removed by the ascertainment of their non-occurrence. Nevertheless, the coincidence of periods assures us that orbital revolution, in one mode or another, prescribes the flow of change. But the ideas so far entertained on the subject scarcely bear examination. Obviously untenable, for instance, is Mr. Roberts's view that the companion of δ Cephei is raised, by the heat received at periastron, from sensible obscurity to a nearly equal grade of lustre with its primary.[2] If this were so a double spectrum

[1] *Astr. Nach.* Nos. 3257, 3338; *Bull. de l'Acad. St. Pétersbourg*, 1894, p. 268; *Astroph. Journ.* vol. i. pp. 160, 263. [2] *Astroph. Journ.* vol. ii. p. 288.

should be observed at quadratures. Again, the maximum should, on the hypothesis, fall short of twice the minimum brightness; actually, it exceeds it three times. Mr. Roberts himself adverts to these objections, but holds them not insuperable. Mr. Eddie's suggestion[1] of luminous increase through intensified tidal action at periastral approach, is more plausible. Bodily strain due to mutual gravitation would, in so eccentric an orbit, gain twenty-seven-fold efficacy as the bodies moving in it come together from its farthest point; and the processes of internal circulation might possibly be sufficiently quickened by the disturbance to yield a largely augmented output of light. But commotions of the requisite violence could not subside with perfect regularity every five days, and they should inevitably be accompanied by gaseous outbursts spectroscopically evident. That they do not occur may be securely inferred from the one circumstance that no trace of emissive symptoms is met with in the light of this star. As to the scale of its system we are, moreover, completely ignorant, and are hence unable to estimate the absolute power over its members of tidal influences. The line-displacements of the bright star acquaint us merely with its rate of motion as projected upon the visual plane; they correspond to a mean orbital radius of 620,000 miles, the real path being perhaps six or eight times wider than that spectroscopically indicated, while the companion-ellipse traversed by the dark satellite may be of any imaginable size. A sapphire-blue star of the sixth magnitude forms with $\delta$ Cephei, which has a golden sheen, a combination resembling that so beautifully exhibited in $\beta$ Cygni.

The variations of $\eta$ Aquilæ are, in every respect, analogous to those of $\delta$ Cephei. They have the same range of 1·2 magnitudes, and a somewhat longer period of $7^d\ 4^h\ 14^m$, which they divide, in about the same proportions, between a rapid increase and a leisurely decay of brightness. The abortive secondary maximum of $\delta$ Cephei, however, develops in $\eta$ Aquilæ into a pronounced recovery of lustre. The light-curve shown in Fig. 22, from Dr. Schur's delineation, renders the duplex phase conspicuous. The binary character of the star was detected by Bélopolsky in 1895,[2] and he computed

[1] *Astroph. Journ.* vol. iii. p. 227. [2] *Ibid.* vol. i. p. 160.

its orbit from improved spectrographic data in 1897.[1] It proved to be of nearly the same *apparent* size as that of $\delta$ Cephei, and the conditions of revolution were, in this case again, manifestly inconsistent with the occurrence of eclipses. An interval of two days was found to separate each minimum from the ensuing conjunction of the bright and dark spheres. Their conjunctions, accordingly, are not transits, since they are unaccompanied by any diminution of light. "Very remarkably," Bélopolsky writes, "the same state of things is present

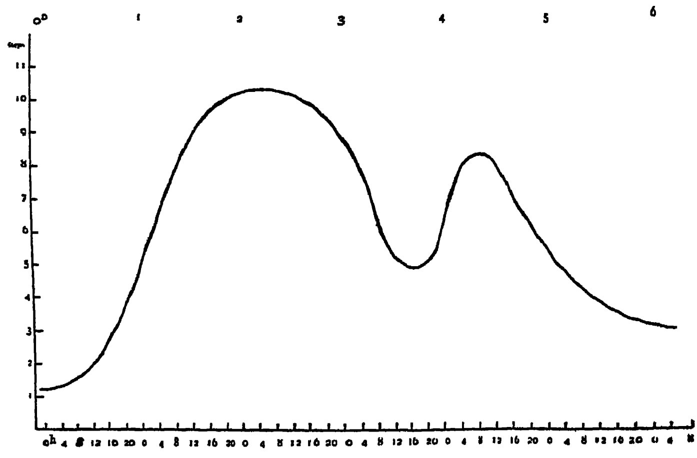


FIG. 22.—Light-Curve of $\eta$ Aquilæ (Schur).

in the variable star $\delta$ Cephei. Hence some other cause must be sought by which the variations in lustre and the spectral displacements of these two stars may be brought into harmony."

Mr. W. H. Wright of the Lick Observatory renewed in 1899,[2] and substantially confirmed the Pulkowa investigations. His orbit, however, came out considerably more eccentric than that computed by his predecessor, and he located its major axis somewhat differently. But on the essential point for the theory of the star's variability—the impossibility of eclipses—they agreed. Fig. 23 reproduces Mr. Wright's drawing of

[1] *Astroph. Journ.* vol. vi. p. 393; *Bull. de l'Acad. de St. Pétersbourg*, t. vii. No. 4, 1900.

[2] *Astroph. Journ.* vol. ix. p. 59.

the ellipse described by $\eta$ Aquilæ round its invisible companion, supposed immovable at the focus (O). Its situation at minimum epochs (marked *Min.* in the figure) obviously corresponds to nearly the highest rate of speed in the line of sight, and to a comparatively wide visual separation of the coupled bodies. The periastron is at P; the points where the secondary phases take place are indicated respectively as *Min.*$_2$ and *Max.*$_2$. They are unaccompanied by irregularities

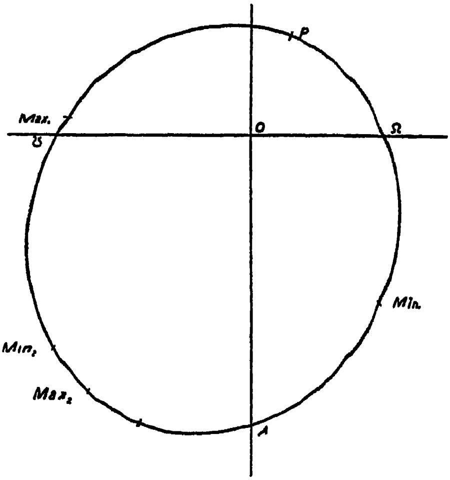



FIG. 28.—Orbit of $\eta$ Aquilæ (Wright).

of movement. In fact, neither in this object nor in the analogous one decorating the crown of Cepheus is there any traceable connection, except their significant agreement in period, between the flow of spectroscopic velocity and the rise and fall of brightness. The spectra of these two variables are quite similar, only the lines of $\eta$ Aquilæ are more diffuse. Both, too, are approaching the sun at uniform rates of about fourteen and nine miles a second respectively. Finally, both are subject to some slight disturbances in time.[1] Those of $\eta$ Aquilæ, discussed by Dr. Lockyer,[2] have an amplitude of five hours, and are self-compensatory in a cycle of 400 light periods.

[1] Chandler, *Third Catalogue*, No. 8073 and *note*.
[2] *Journ. Brit. Astr. Assoc.* vol. vii. p. 471.

The generalisation is a tolerably safe one that all Cepheid stars are binaries; but its establishment must be a work of time. Those of the shortest periods are the most promising for purposes of spectrographic inquiry, since they are likely to be in swift circulation, and hence to show conspicuous line-displacements. Negative results, however, as already said, may simply imply an unfavourable situation of the orbits; they do not necessarily indicate the solitary condition of the stars. A few examples of Cepheid variables are given below in the order of increasing length of period. Some brief description of the peculiarities of each follows.

| Name. | Limits of Change. | Period. d. h. m. |
|---|---|---|
| R Muscæ | 6·6 to 7·4 mag. | 0 21 10 |
| R Trianguli Australis | 6·6 „ 8·0 „ | 3 9 20 |
| ST Cygni | 6·6 „ 7·4 „ | 3 20 10 |
| T Vulpeculæ | 5·5 „ 6·5 „ | 4 10 28 |
| Y Sagittarii | 5·8 „ 6·6 „ | 5 18 33 |
| U Sagittarii | 7·0 „ 8·3 „ | 6 17 46 |
| X Sagittarii | 4·0 „ 6·0 „ | 7 2 50 |
| W Sagittarii | 4·8 „ 5·8 „ | 7 14 16 |
| S Sagittæ | 5·6 „ 6·4 „ | 8 9 7 |
| X Cygni | 6·4 „ 7·7 „ | 16 9 15 |
| W Virginis | 8·7 „ 10·4 „ | 17 6 30 |
| T Monocerotis | 5·8 „ 8·2 „ | 27 0 18 |

R Muscæ, being circumpolar at the Cape, can be observed to advantage only in southern latitudes. Once in twenty-one hours it doubles its light, and so emerges into naked-eye visibility, then sinks back again out of sight. The rise occupies just seven hours, or one-third of the period—the normal proportion for stars of this class. Evidence of rapid circulatory motion is pretty sure to be elicited by spectrographic means.

The phases of R Trianguli Australis were noticed by Gould in 1871, and have of late engaged the attention of Roberts. They show the peculiarity, surprising in a Cepheid star, of being uncertain in extent. The full measure of change is from 6·6 to 8·0 magnitude, but at certain maxima it mounts no higher than 6·8; at certain minima it descends no lower than 7·5 magnitude. It would be of interest to

learn whether these oppositely incomplete phases occur together or disconnectedly. No methodical account of them has, we believe, been published. The increase of brightness in R Trianguli occupies little more than one quarter of the period.

The light-curve of ST Cygni is "humped" like that of δ Cephei. About forty-six hours after maximum the decline is stayed, then, a brief pause ended, resumes its course. The interval from minimum to maximum is 21½ hours, that from maximum to minimum seventy.[1] The variability of this star[2] was detected at Potsdam in 1896 by G. Müller and P. Kempf.

The spectrum of T Vulpeculæ is similar to that of δ Cephei.[3] Its changes, discovered by Sawyer in 1885, consist in a rise of one magnitude in $1^d\ 7^h$, followed by subsidence in $4^d\ 3^h$. The comparative brightness of the star brings its movements well within range of spectroscopic investigation.

The four stars in Sagittarius, which come next on our list, form a singular group, discovered by Schmidt in 1866.[4] They are included in a space of about ninety square degrees, and all vary after the fashion of δ Cephei in periods comprised between 5·8 and 7·6 days. Among them X Sagittarii, which attains once a week fourth-magnitude rank, is the most conspicuous. Its spectrum is of the solar type. One of its associates, U Sagittarii, distinguished by a strong orange tint, is the centre of a little cluster. Its fluctuations, upward in 2½, downward in 4¼ days, proceed with the regularity of clockwork.

S Sagittæ shows the retarded decrease and inflected curve distinctive of its class.[5] Yendell considered the maximum to be double (see Fig. 24). The change at minimum is unusually slow. In quality of light the star was found by Sir Norman Lockyer to be an exact match for δ Cephei.

[1] *Astr. Nach.* No. 3483; Luizet, *ibid.* No. 3570; Flanery, *Knowledge*, vol. xxiii. p. 134; *Harvard Circular*, No. 41.

[2] Sometimes designated SU Cygni.

[3] Lockyer, *Proc. Royal Society*, vol. lix. p. 101.

[4] Its fourth member, Y Sagittarii, was added by Sawyer in 1886, *Astr. Journ.* No. 328; Yendell, *Pop. Astr.* vol. ii. p. 364.

[5] Chandler, *Astr. Journ. Nach.* No. 2749; Yendell, *Astr. Journ.* Nos. 157, 321; *Pop. Astr.* vol. ii. p. 207.

X Cygni was discovered by Chandler in 1886. It rises without fail in $6^d\ 19^h$ to 6·4 magnitude, but shows an inconstant minimum brightness, sometimes descending to 7·7, at others stopping short at 7·2 magnitude. The period of $16^d\ 9\frac{1}{4}^h$ is not known to vary. The star is quite colourless; information as to the character of its spectrum is not at present forthcoming.

W Virginis is uncertain both at maximum and minimum. Its highest rise is to 8·7, its lowest descent to 10·4 magnitude. But these limits are far from being always reached; phases deficient by quite half a magnitude either way are often observed, and seem to intervene casually. The period, on the other hand, of $17^d\ 6\frac{1}{2}^h$ is strictly conformed to.

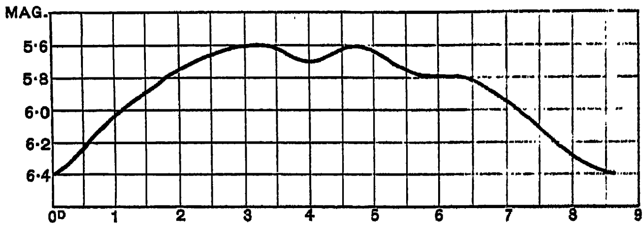



FIG. 24.—Light-Curve of S Sagittæ (Yendell).

The time of increase, $8^d\ 5^h$, is proportionately long for a Cepheid variable.

That of T Monocerotis is, on the contrary, relatively short, although the entire cycle of twenty-seven days is the most protracted yet ascertained for a star of its class. And here again the amplitude of change is inconstant. Maxima occur as high as 5·8, as low as 6·4 magnitude, while the minimum brightness ranges between 7·4 and 8·3 magnitude. There are then spring and neap tides of stellar fluctuation; yet no clue can be found to the cause of their difference. The four Cepheid variables in which they appear—namely, R Trianguli, X Cygni, W Virginis, and T Monocerotis—have no other features visibly in common. Perhaps the spectroscope may reveal unlooked-for analogies connecting their physical qualities or their systematic relations; but its dicta have still to be pronounced.

About three dozen stars had been registered at the close

of last century as variable on the model of $\delta$ Cephei. Most generalisations regarding them are liable to lose validity by future experience; but there are two properties in the absence of which they should be otherwise classified. In all, light-change progresses unceasingly; in all, it advances more rapidly in the direction of increase than of decrease. An inclination, more or less accentuated, to pause in descent is probably connected with this kind of dissymmetry. Among their other distinctive qualities the following may be provisionally enumerated:—(1) Their spectra are of the solar type. (2) They are binaries revolving in the periods of variation. (3) They are not eclipsing pairs; their orbits may be inclined at any angles to the visual plane. (4) Their fluctuations in lustre are unaccompanied by spectral change. (5) Being nearly devoid of proper motion, they are presumably at vast distances from the earth. They are then giant suns.

Future research will decide whether Cepheid stars are marked off from ordinary spectroscopic binaries by any peculiarities in their manner of circulation. Are their orbits, for instance, in all cases highly eccentric? Is there a fixed relation between the situation of the periastron and the point of lowest brightness? Do the major axes revolve? Above all, what differentiates short-period variables from revolving pairs constant in light? Why do $\delta$ Cephei and $\eta$ Aquilæ show an incessantly changing lustre, while Polaris and $\theta$ Ursæ shine steadily? The four appear to be of analogous constitution, and to suffer no diminution by eclipse. What form of influence, then, is it which acts so strikingly upon the two former objects, while leaving the two latter unaffected? Undoubtedly the close attendance of a satellite is instrumental to the production of the observed changes of luminosity; but other conditions also come into play—conditions that are absent in Polaris, in $\beta$ Aurigæ, in $\alpha$ Virginis, in $\theta$ Ursæ, in $\theta$ Draconis. What is their nature? Here is the main issue as regards short-period variability.

# CHAPTER XX.

## SHORT-PERIOD VARIABLES—*Continued.*

THE second family of short-period variables resemble the first in the continuous nature of their fluctuations. They are distinguished from them by the symmetrical apportionment in time of those fluctuations. The intervals from minimum to maximum, and from maximum to minimum, are almost exactly equal. Not very many such stars are known. First singled out as rarities by Dr. Chandler in 1896,[1] they have for their exemplar ζ Geminorum.

The variations of this star, discovered by Schmidt in 1847, carry it from 4·5 to 3·7 magnitude in five days and twenty-two minutes, and back again to its former level in a space of time just three hours longer. The difference may be called negligible. Fig. 25, A, shows the representative light-curve. Its undulations at present succeed each other without sensible alteration; but observers of an earlier generation regarded them as subject to disturbance. Their period, according to Argelander, was ten minutes longer in 1869 than it had been in 1847;[2] and Schmidt pronounced the fluctuations in brightness to be nearly suppressed in 1868, and irregular in 1881.[3] Fresh interest was imparted to the history of the star by Bélopolsky's detection, early in 1898, of its composite nature;[4] and the discovery, which had not been published, was repeated a year later by Campbell at Lick. He remarked besides unaccountable deviations from the even pace of elliptical progression, established as genuine by critical test-observations. Their nature will be seen at a glance by a

[1] *Astr. Journ.* No. 374.
[2] *Bonner Beob.* Bd. vii. p. 393.
[3] *Astr. Nach.* Nos. 1745, 2420.
[4] *Ibid.* No. 3565.

reference to Fig. 25; the lower curve in which (B) represents the radial velocities of ζ Geminorum. The unit of time is one day, the unit of speed five kilometers per second. A comparison with the upper curve (A) shows that the period of motion agrees with the period of light, but that its rate varies oppositely to the brightness—that is to say, the star is moving rapidly in the line of sight just when its minima take place. They are, accordingly, not due to eclipses, which should coincide absolutely, or very approximately with zero radial velocity. The relations of the pair are made still clearer by Professor Campbell's drawing of the orbit deduced from the velocity-curve (see Fig. 26). It represents that of the bright com-

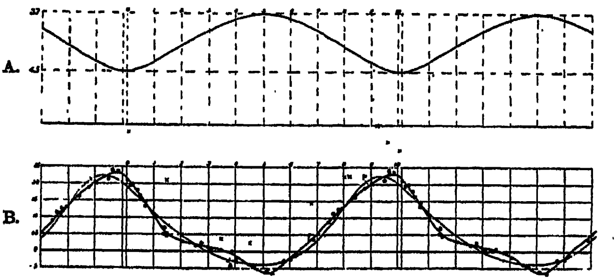



FIG. 25.—Curves representing the Variations (A) in Light, (B) in Radial Velocity of ζ Geminorum (Campbell).

ponent round the centre of gravity, while the similarly shaped path followed by the dark star must be larger or smaller in the inverse ratio of its mass. The ellipse depicted in Fig. 26 has an eccentricity of 0·22; PA is the line of apsides, OE the line of sight. Minima occur $1^d\ 7^h$ after periastron at the point *Min.*; and since the companion is then situated somewhere in the direction *Om*, its interposition is evidently out of the question. Recurring now to Fig. 25, B, we perceive that the heavy black line connecting the points determined by actual measurement, pursues an undulating course. In Professor Campbell's words, "The observed velocity-curve is alternately above and below the elliptic curve, and the intersections of the two occur at approximately equal intervals of time. There are six of these intersections, corresponding to three complete periods or cycles in one period of the light-

curve." The oscillations showed no signs of intermission during fifteen months, and assuredly indicate an inherent peculiarity of the system. They might be formally explained by assuming it to be triple, the bright star revolving in $3^d\ 9\frac{1}{4}^h$ round one invisible attractive mass, and the two together in $10^d\ 3\frac{1}{2}^h$ round another more distant. But the arrangement, as Professor Campbell points out,[1] could scarcely be stable, owing to the commensurability of periods, and the consequent subversive piling-up of disturbances. Nor is it

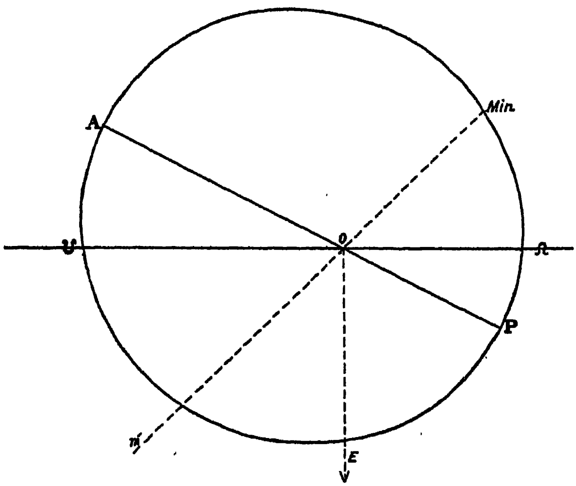



FIG. 26.—Orbit of ζ Geminorum (Campbell).

easy to accept the idea that the digressions of ζ Geminorum from a mean rate of travel are "minor tidal effects." Prolonged and diversified researches are, in fact, needed before any promising theory of them can be formed.

The star is of a golden yellow colour. Its spectrum is a replica of that of δ Cephei. An annual proper motion is attributed to it of 0·0165″, but the value is too small to be altogether reliable. The remoteness of this problematic system is hence unimaginably great.

The following brief list of Geminid variables, with some ensuing comments, will serve to widen the reader's acquaintance with the characteristics of the species.

[1] *Astroph. Journ.* vol. xiii. p. 94.

| Name. | Limits of Change. | Period. |
|---|---|---|
| | | d. h. m. |
| $R^2$ Centauri | 7·4 to 7·8 mag. | 0 7 16 |
| S Antliæ | 6·7 ,, 7·3 ,, | 0 7 47 |
| U Pegasi | 9·3 ,, 9·9 ,, | 0 9 0 |
| 24 ω Centauri | 13·4 ,, 14·0 ,, | 0 11 5 |
| V Puppis | 4·1 ,, 4·9 ,, | 0 17 27 |
| U Vulpeculæ | 6·9 ,, 7·6 ,, | 8 0 4 |
| *d* Serpentis | 5·0 ,, 5·7 ,, | 8 17 17 |
| β Lyræ | 3·4 ,, 4·5 ,, | 12 21 47 |

The variability of $R^2$ Centauri, discovered by Mr. A. W. Roberts in 1896,[1] is slight but sure, and proceeds by evenly measured steps of increase and decrease. The period is the shortest found for any star outside the precincts of a cluster. With its companion, should it prove to be spectroscopically double, $R^2$ Centauri must form an exceedingly close, or an enormously massive pair.

S Antliæ bore for eight years the reputation of being an Algol variable.[2] The shortness of the period and the flatness of the curve, conveying the impression of a stationary maximum, produced a deception removed in 1896 by the Harvard photometric results. They showed the light-change to advance continuously along a smooth curve, unbroken by the sudden drop indicative of an eclipse. It is, however, marked by the "interesting feature" (in Professor Pickering's words[3]) "that the time of increase occupies 0·62 of the entire time of variation." Here then is an ostensible case of dissymmetry opposite to the usual kind. But the relation was stated by Mr. Sperra of Randolph, Ohio, to be inconstant, and he deduced from his observations an average equality of the intervals between opposite phases.[4] This is perhaps the essential fact. S Antliæ is a white star with a transition-spectrum[5] resembling that of Procyon. The lines are never seen double, so that two bright components cannot be present unless they revolve in a plane nearly at right angles to the visual ray. But line-displacements due to

[1] *Astr. Journ.* Nos. 378, 384; *Astroph. Journ.* vol. x. p. 312; *Nature*, vol. lxiv. p. 469. [2] *Astr. Journ.* vols. ix. pp. 180, 183, 190; x. p. 11.
[3] *Astroph. Journ.* vol. iv. p. 141. [4] *Astr. Journ.* No. 413.
[5] Pickering, *Astr. Nach.* No. 3008.

motion round an obscure body, may possibly be detected by the application to this curious object of a slit-spectroscope.

A small star in Pegasus was noticed by Dr. Chandler in 1894 as apparently subject to eclipses; but its waxings and wanings proved, on fuller inquiry, to be without pause. A controversy as to their nature[1] was practically terminated by Mr. Wendell's measures with the polarising photometer at Harvard College in December 1897.[2] Their upshot is graphically exhibited in Fig. 27. Each of the closely set dots through which the curve was drawn represented eighty settings made on eight nights, none being rejected

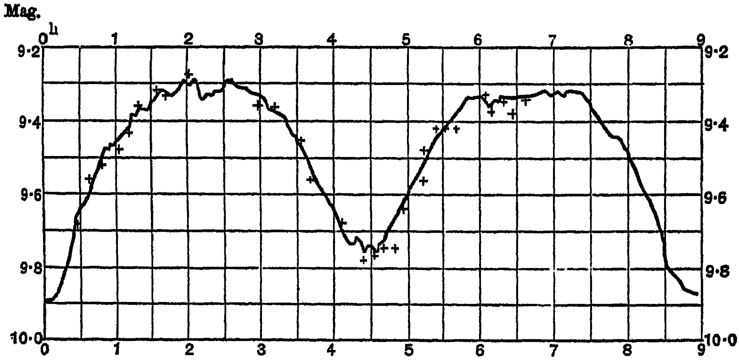



FIG. 27.—Photometric Curve of U Pegasi (Pickering).

for discordance. The crosses, each of which gives the average of sixteen settings, embody single nights' results. The divisions in time (abscissæ) represent intervals of thirty minutes; the divisions in brightness (ordinates), tenths of a magnitude. The complete period of the star is nine hours less nine seconds, but it is nearly cut in two by a secondary decline falling short of full minimum by only 0.15 of a magnitude. The reality of this trifling difference, contested by Chandler, appears to be substantiated by the Harvard data, and stamps U Pegasi as of the kindred of β Lyræ, the premier short-period variable. A mathematical discussion of the conditions of U Pegasi, based upon the eclipse-theory, was published in 1898 by Mr. G. W. Myers of the Yerkes Observatory.[3] It is valuable as an authoritative proposal of the terms demanded

[1] Chandler, *Astr. Journ.* Nos. 358, 374, 426.

[2] *Harvard Circular*, Nos. 23, 25.

[3] *Astroph. Journ.* vol. viii. p. 163.

by that theory under the given circumstances. They are not wholly unacceptable. They involve, at least, no contradiction of any known law of nature; yet they are difficult to imagine realised. The system must obviously be composed, if its luminous variations be geometrically explicable, of two bright bodies revolving almost in contact. Indeed, they are probably *more than in contact*, if the assumed data are correct; they interpenetrate and together form an "apioid," which, according to Poincaré, is a figure of equilibrium for rotating masses. One of the conjoined globes proved, moreover, to have a radius about four-fifths that of its primary, and to be less intrinsically brilliant in sensibly the same proportion. Their revolutions in a period of nine hours afford eclipses, alternately total and partial, at intervals of four and a half hours, the orbit being viewed by us edgewise. Now such an arrangement as that indicated for U Pegasi might conceivably prevail in an embryonic binary system. It would, in fact, accord well with Dr. See's views as to the evolution of double stars; but evidence of its actual existence is still a desideratum. Until affirmed by the spectroscope, it must be treated as only a speculative possibility; and the example of $\zeta$ Geminorum is not encouraging to the occultation-rationale of continuous variability. The time, however, is not far distant when the decisive motion-test will be applied, if not to this faint object, at any rate to others that are analogous and more accessible.

Some few of the variable stars in clusters belong to the Geminid class. An example is afforded by No. 24 in the great southern star globe $\omega$ Centauri. One of five or six thousand silvery specks crowded together into the "span of a man's hand," it yet preserves individuality. Once in $11^h\ 5^m$ it gains twofold brightness, then fades even more rapidly than it increased.[1] The changes are said to resemble those of S Antliæ. If occasioned by the uninterrupted mutual eclipses of equally luminous bodies, a mean density would be implied for them of one-fifth the solar. And this irrespectively of their mass. In a system composed of a pair of globes revolving just in contact, density depends solely upon period.[2] The reason is easily seen. With a constant period the mass of

[1] *Harvard Circular*, No. 33; *Harvard Annals*, vol. xxxviii. pp. 144, 160 (Bailey).

[2] Cf. *Observatory*, vol. xx. p. 54.

a system varies as the cube of the distance, and in the same proportion the component spheres must, if they remain contiguous, vary in bulk. Thus, since volume and mass preserve under these circumstances a fixed ratio, density is the same for any assignable value of their absolute amounts.

A variable star, more than commonly enigmatical in its procedure, comes next on our list. Discovered by Mr. Stanley Williams in 1886,[1] V Puppis fluctuates between 4·1 and 4·9 magnitude in a period fixed by Mr. Roberts, with vigilant care, at $17^h\ 27^m\ 13^s$. The alternate minima are slightly unequal, and he assumes them to correspond to a trifling disparity in brightness between the members of a mutually occulting "dumb-bell" combination revolving in double the light-period, or $1^d\ 10^h\ 54\frac{1}{2}^m$.[2] But here the spectroscope intervenes. From an examination of spectrographs taken by Bailey at Arequipa, Professor Pickering inferred in 1896[3] the binary character of the star. During thirty-seven hours at a stretch it shows double absorption lines, which then close up, and after a brief interval open out again, this time with the fainter component in the reversed position. These shiftings to and fro take place in a cycle of $3^d\ 2^h\ 46^m$, and indicate a relative velocity of 385 miles a second, giving a minimum value for the radius of the orbit of 16,500,000 miles, and a combined mass seventy-seven times that of the sun. Have we then, in V Puppis, a genuine instance of discrepancy between the motion and light-periods? Or is their eventual reconcilement probable? Mr. Roberts has spoken his last word on the subject, and the spectrographic data seem sure. Yet if any compromise were possible, it should be, one would suppose, by subdividing the longer period, not by extending the shorter one. The anomaly of their discordance is too flagrant to be admitted without cogent proof.[4]

The variations of U Vulpeculæ proceed equably, according to their discoverers, MM. Müller and Kempf,[5] in a period of eight days. M. Luizet of Lyons agrees, and regards them as

[1] *Astr. Nach.* No. 3410.

[2] *Astr. Journ.* No. 477; *Astroph. Journ.* vol. xiii. p. 177; *Nature*, 12th September 1901.

[3] *Harvard Circular*, No. 21.

[4] Since the above was written, Miss A. J. Cannon has made the brief statement (*Harvard Annals*, vol. xxviii. p. 177) that the $34^h$ period satisfies all observations.

[5] *Astr. Nach.* No. 3483.

strictly conformable to those of $\zeta$ Geminorum.[1] The Harvard measures, nevertheless, indicated an accelerated increase.[2] If it be substantiated, the star should rank as intermediate between the Cepheid and the Geminid families.

The instability of *d* Serpentis, suspected at Potsdam in 1891, was verified by Yendell in 1894.[3] Its phases, as determined by him, resemble those of $\beta$ Lyræ. They include a secondary minimum, symmetrically placed between two equal maxima. The spectroscopic investigation of this star, which never descends so low as the sixth magnitude, should present few difficulties, and will be of special interest from the side-lights it may throw on the problem of the Lyre variable. This latter subject is so complex as to demand treatment in a separate chapter.

Another inviting object to the possessors of spectrographic apparatus is the southern variable $\kappa$ Pavonis. It ranges from 3·8 to 5·2 magnitude in a period of nine days two hours, but by gradations lacking distinctive character. Their correlation with spectral line-shiftings might serve more clearly to define their nature. Physically, the star belongs to the solar family.

One of the many singularities connected with stellar variation is that it takes a special form in condensed clusters.[4] Even in them this form does not prevail universally; sporadic cases of many kinds are met with; but in general the light change of aggregated stars has the following characteristics. The periods are extremely short. They average half a day in "Messier 5," and 90 out of 132 determined for the components of $\omega$ Centauri fall below twenty-four hours.[5] The rise to maximum is wonderfully swift. One-tenth part of the cycle is about the proportion claimed by it, and No. 45 $\omega$ Centauri increases by two magnitudes in the space of one hour. The minima are prolonged dead-level tracts. In other words, the variation is discontinuous. It might be described as a sudden leap upward into comparative brightness from a habitually low state. The maxima are episodes, foreign, as it were, to the internal economy of the stars. They recur, nevertheless, with the utmost precision. Hundreds, nay, thousands of successive periods have been watched without the detection of the smallest

[1] *Astr. Nach.* No. 3570. [2] *Harvard Circular*, No. 41.
[3] *Astr. Journ.* No. 331. [4] S. I. Bailey, *Astroph. Journ.* vol. x. p. 257.
[5] S. I. Bailey, *Harvard Annals*, vol. xxxviii. p. 209.

irregularity. The light-curves of two stars in Messier 5 are given in Fig. 28 from Professor Bailey's drawings. Each has a range exceeding one magnitude, and a period of approximately twelve hours.

The discovery of "cluster variables" as a class apart was made by Professor S. I. Bailey in the course of his photographic work at the equatorial station of Harvard College. They literally swarm in certain groups, while in others they occur scantily or not at all. An isolated southern star, S Aræ, the character of which was detected by Innes, and has been investigated by Roberts,[1] appears to be of their type. Ordinarily hibernating near the eleventh, it springs up to 9·5 magnitude,

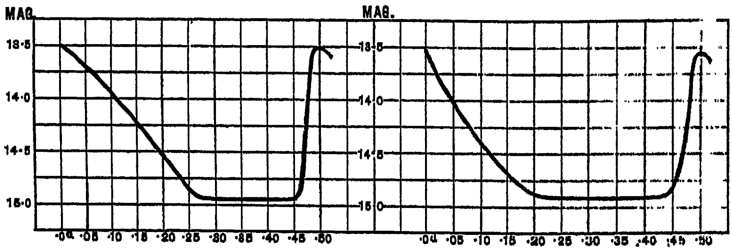



FIG. 28.—Light-Curves of Cluster-Variables (Bailey).

at the rate of a magnitude in twenty minutes, once in eleven hours. U Leporis, over which Mr. Innes has kept watch, approximates to the same type. This mode of variation is peculiarly difficult to explain. Eclipses will not here serve our turn; however modified, they evidently fail to meet the requirements of the situation.[2] The phenomena, indeed, to a certain extent, invert those with which eclipses are associated. Instead of an abrupt failure, a sudden access of light has to be accounted for. The question whether such stars are binaries is of great interest. Cluster-components, which are rarely brighter than the thirteenth magnitude, can indeed scarcely be expected to furnish a reply to it; but something definite on the point may be learned by a spectrographic appeal to S Aræ. The direction that should be given to further inquiries will then become apparent.

[1] *Monthly Notices*, vol. lxi. p. 163.
[2] Bailey, *Harvard Annals*, vol. xxxviii. p. 234.

# CHAPTER XXI.

## THE PROBLEM OF BETA LYRÆ.

On the 10th of September 1784, John Goodricke of York, a deaf-mute scarcely twenty years of age, perceived the second brightest star in the Lyre to be variable. He ascertained, further, the main features of its light-change. They are very peculiar.[1] Four phases of approximately equal duration are comprised in a period of twelve days and nearly twenty-two

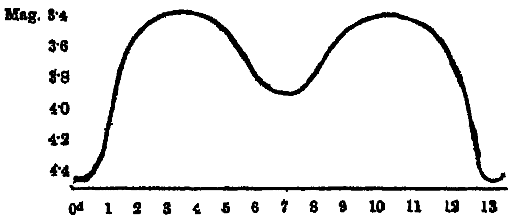



Fig. 29.—Light-Curve of $\beta$ Lyræ (Argelander).

hours. They are portrayed in the symmetrical curve drawn from Argelander's observations in Fig. 29. The twin maxima, situated midway between the principal and secondary minima, are of absolutely constant brilliancy. Constant, too, is the chief phase of obscurity, so that the compass of variation, from 3·4 to 4·4 magnitude, is a fixed quantity. The intermediate minimum, however, is not so immutable. Defect and excess are occasionally observed in it. But the flow of change is always smooth and uninterrupted. Nor is there any pause in a slow lengthening of the period, which has progressed, during the last hundred years, at the average rate of about

[1] See *Knowledge*, vol. xvii. p. 128 (A. M. Clerke).

one-third of a second at each recurrence. That the disturbance will prove compensatory can scarcely be doubted; but the law of restoration is not yet apparent.

The spectrum of β Lyræ is dominated by helium. It includes members of all the six series emanating from that substance, and they are mostly composite aggregations of bright and dark rays.[1] The Huggins series of hydrogen is similarly represented; among metals, calcium and magnesium are prominent, and ten dark oxygen lines in the ultra-violet were photographed at Tulse Hill in 1899.[2] But the special characteristic of this spectrum is its variability. The coupled lines are neither fixed in position nor constant in structure. They shift, they split, they flash and fade; they spread into diffuse bands or contract to definite filaments; and this in obvious, though disturbed, subordination to the light-period of the star. The two kinds of variation are, to some extent, mutually dependent; yet they are far from showing a strict concurrence. The loose and indeterminate nature of their relations places formidable obstacles in the way of investigating either.

Already, in 1866, Father Secchi noticed bright lines in the dispersed light of β Lyræ, and Von Gothard was struck in 1883 with their unaccountable fluctuations of visibility.[3] But the complexities they presented wholly baffled direct observation; their unravelment only began to be possible when spectrographic methods became fully developed. Through Mrs. Fleming's examination of the Harvard plates, it was made evident in 1891 that the emission-rays had dark companions, and were not stationary with regard to them; and Professor Pickering[4] gathered from their displacements the probability that the two sets belonged severally to the unlike components of a close binary, revolving synchronously with the ebb and flow of total brightness. He estimated their relative velocity at 300 miles a second in a circular orbit, with a radius of 50,000,000 miles. This hypothesis is beyond question founded in fact. The star is composite, and the emissive and absorptive elements of its

[1] Frost, *Astroph. Journ.* vol. ii. p. 383.
[2] *Astr. Nach.* No. 3565.
[3] *History of Astronomy*, 4th ed. p. 379 (A. M. Clerke).
[4] *Astr. Nach.* No. 3051.

spectrum shift, on the whole, oppositely; each battalion, as Mr. McClean has indicated, moves as a unit, and in a contrary sense to the other. To distinguish them ought then to be a simple matter. The differently affected lines ought of themselves, one might expect, to declare their separate origin. Difficulties well-nigh insuperable, nevertheless, beset the interpretation of this spectrum. Their main source is this. The constituent lines do indeed oscillate through motion, but they are subject to further influences of a more complex kind, and of a barely conjecturable manner of working. The various species of change are hence entangled and disguised to a bewildering extent; and totally divergent views have been expressed as to the proper apportionment of the spectrum between the bodies jointly originating it. Sir Norman Lockyer attributes the absorption lines to a pair of "Orion" stars, unequally advanced in development,[1] with a relative velocity of 156 miles a second; and the addition of a bright-line companion is an implied necessity of his scheme. Mr. McClean[2] demands a dark-line and a bright-line component, mutually circling at a speed of 400 miles a second. Miss Maury considers that three stars must be engaged.[3] Dr. Vogel[4] and Father Sidgreaves,[5] although they have investigated the spectrum in detail, make no attempts at its analysis. M. Bélopolsky, by minimising the scope of attack, made a substantial advance towards the solution of the problem.[6] He dealt with only two lines—the absorption ray of magnesium at λ 4482 and the brilliant F of hydrogen; but succeeded in establishing, it might be said, incontrovertibly, their separate production from conjoined bodies dissimilarly constituted. The magnesium line is better adapted for measurement than most of the spectral elements of β Lyræ; it is subject to only moderate alterations in width and definition, and determinations of its motion-shifts afford, accordingly, consistent results. From them Bélopolsky has calculated the orbit of the originating globe, which may be identified with

[1] *Astr. and Astrophysics*, vol. xiii. p. 575.

[2] *Monthly Notices*, vol. lvii. p. 6; *Observatory*, vol. xx. p. 87.

[3] *Harvard Annals*, vol. xxviii. p. 103.

[4] *Sitzungsberichte*, Berlin, 8th Feb. 1894.

[5] *Monthly Notices*, vols. liv. p. 94; lvii. p. 515.

[6] *Memorie degli Spettroscopisti Italiani*, t. xxvi., June 1897.

Lockyer's Rigel star. He found it to be but slightly eccentric ($e = 0·04$); the mean radius (supposing the plane to coincide with the line of sight) is 15,000,000 miles; the system is advancing towards the sun at the rate of seven miles a second, and the times of zero radial velocity agree so nearly with the epochs of minimum as to lend countenance to the eclipse-rationale of light-failure. A second orbit was then computed—though far less securely—for the component showing bright F, each being described round the common centre of gravity. It proved to be about half the size of the former, which implied that the body travelling in it (designated A) was twice as massive as the companion (B). It possesses, in fact, the gravitating power of eighteen, the latter of nine suns. Nevertheless, the principal minimum corresponds to the obscuration of the minor globe, while at the secondary phase, the primary star is the one partially occulted. The bright-line star, A, must then be much less luminous in proportion to the quantity of matter it contains than the dark-line star, B. This does not appear probable, but it cannot be pronounced impossible.

On the whole, Bélopolsky's results are plausible, and the basis they rest upon is solid, if narrow. Yet the development of their consequences leads to a network of perplexities. The star A, characterised by hydrogen-emission, can be no other than Lockyer's second dark-line star—that resembling Bellatrix; but if so, "the bright bands," as Miss Maury says, "have a residual motion of their own, which places them sometimes towards the red, and sometimes towards the violet end of their own system of dark lines, and at other times upon the lines of one, or both spectra." Yet the suggested triple combination is inadmissible. The presence of a third body would require the introduction of a second period, and of this no trace is discernible. The spectral phenomena are in many ways abnormal and unaccountable, but in the long run they conform to the single and nearly uniform time-measure of the system, and preserve a modified fidelity to the course of its light-change. Gravitational disturbances, too, might be expected to betray the influence of an extra member, and none have been detected; for the slight retardation now going forward is otherwise explicable. We seem prohibited

from carrying the subdivision of $\beta$ Lyræ any further than into a pair of globes, exemplifying distinct varieties of the Orion spectral pattern, one or both vivified by a range of bright lines.

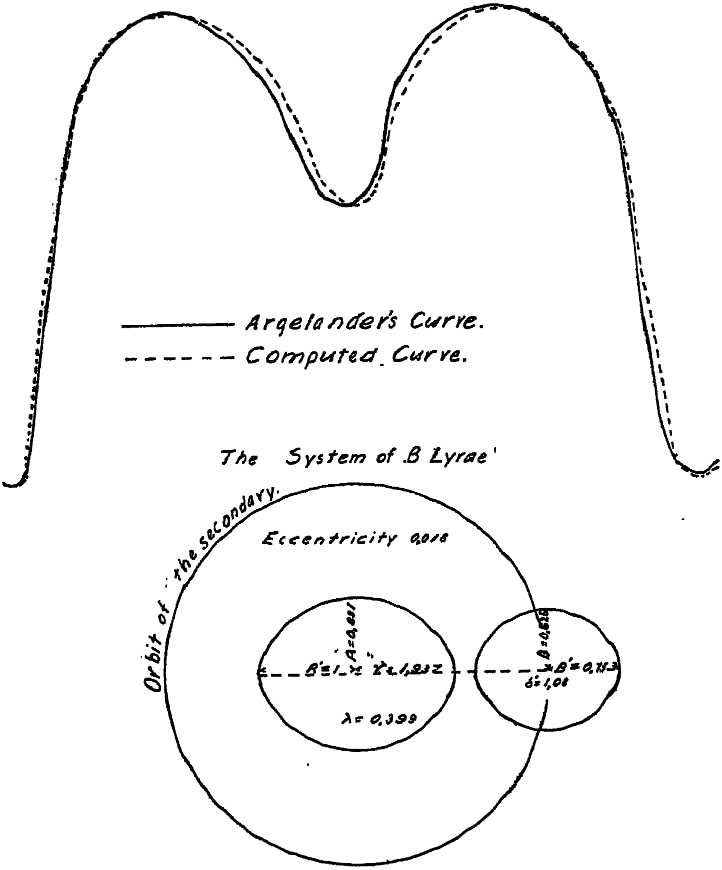



FIG. 30.—System of $\beta$ Lyræ (Myers).

An effort was made by Mr. G. W. Myers in 1897[1] to bring this star's variations within the explanatory scope of the "satellite-theory." By suitably combining effects of occultation with effects of tidal deformation, he showed that the observed periodicity could be represented with the satisfactory exactitude conveyed in the upper section of Fig. 30,

[1] *Astroph. Journ.* vol. vii. p. 1.

the lower section of which exhibits his plan of the supposed orbit and its egg-shaped occupants. Evidently, when they are seen *broadside on* there is full light, while a minimum attends an *end-on* view of them. And this altogether apart from possible eclipses. If these occur as well, the effects reinforce each other; while those due to the gradual turning of the discs soften off the abruptness of occultation-phases, and thus serve to give the light-curve its smooth character. The mutually eclipsing spheroids must, however, be extremely close together, if they do not actually coalesce. Combining, on the questionable assumption of their congruity, the displacements of F measured by Bélopolsky with those attributed by Lockyer to three dark lines, Mr. Myers found the masses of his two stars to be respectively twenty-one and ten (nearly) in terms of that of the sun, and determined the radius of their joint orbit at 31,000,000 miles. Their mean density proved to be lower than that of air at sea-level, and suggested a "nebulous condition." Indications were even discerned of a process of separation between the components, scarcely yet, or just recently accomplished. "In either case," Mr. Myers adds, "we seem to have here the first concrete example of a world in the act of being born." And it cannot but be noted with profound interest that "an attempt at a formal representation of the condition of things prevailing in the system of $\beta$ Lyræ leads to the assumption of a single body, such as Poincaré's or Darwin's figures of equilibrium."

Yet the "formal representation" in question is difficult to accept as a physical actuality. The extreme tenuity attributed by it to a star shining with vivid lustre almost defies credence, yet is an inevitable consequence of the satellite-hypothesis of variability. Where there is no halt in change, there can be only a transient cessation of eclipse, and the revolving globes must be virtually in contact. But under these circumstances, their density, as we have seen, is a function of the period alone; and thirteen days is long compared with the nine hours of U Pegasi, for which star the upshot of a similar experimental investigation has been recorded. This theory, moreover, takes account only of the optical changes in $\beta$ Lyræ. Occultation-effects, distortion-effects, and motion-displacements of spectral lines are of this

kind. They imply no intrinsic alteration. They are compatible with an absolute constancy in the state of the system; they depend merely upon the visual relations to ourselves of the bodies forming it. They are accordingly calculable and measurable. Exactly what sort and amount of fluctuations they are capable of producing, can be ascertained from given data. But with the physical influences of close duplicity upon radiation we have only a speculative acquaintance. And in the present case, those that might be due to unequal tidal disturbances are excluded by the circular shape necessarily ascribed to the path of a star noted for the equal duration of all its phases. Intrinsic variations in its spectrum are, nevertheless, glaringly apparent, and they tend to recur cyclically in just thirteen days. We spare our readers the bewilderment of their minute description, asking them instead to fix their attention on a few salient points.

Let us consider, for instance, the spectral symptoms at the critical epoch of chief minimum. Almost as a matter of course, the continuous radiance has faded; sixty per cent of it is intercepted or otherwise suppressed. This is, in fact, the essential cause of the falling-off in brightness. What is distinctive is that the emission-lines have become narrower, sharper, and fainter than usual; they are considerably shifted towards the red, and strongly developed dark companions, in their normal places, are attached to their more refrangible sides. Now the downward shove of the whole range of bright lines is either due to motion, or it is not. If it is, the emitting body is travelling rapidly away from the earth at the time of the supposed eclipse, which must accordingly be dismissed as fictitious. If, on the other hand, the alteration of wave-length denotes physical action of some kind in the atmosphere of the star, then inferences as to its orbital revolution, since they have only a spectroscopic warrant, are highly precarious. The possibility, to be sure, may be admitted that the dark lines shift optically, the bright lines physically *and* optically; but the distinction has an air of arbitrariness which does not recommend its confident adoption.

Another significant circumstance is that the spectral appearances at the secondary minimum and at the ensuing

maximum are much alike. The most characteristic among them is the projection of a black line centrally upon a wide bright band. Dr. Vogel's drawings of the first ultra-violet hydrogen line (H $\zeta$) at these successive phases are reproduced in Plate XVI., Figs. 1 and 1a. Here, at any rate, a single light-source is concerned. A moment's consideration suffices to show that a dark line in the spectrum of one star cannot cut a slice out of a brilliant band proceeding from another. Absorption implies real superposition of the arresting and absorbing layers. The effect observed is then one of reversal. It arises through the stoppage by a cooler stratum of hydrogen of the emissions from a denser and hotter underlying stratum in the same stellar atmosphere. Fig. 2 in the same Plate represents, from a drawing by Professor Keeler, the "D lines" in $\beta$ Lyræ at principal minimum. It was made with the great Lick refractor, 14th and 15th November 1889, and shows the sodium pair to the right merged into a dark, hazy band, with above it $D_3$ brilliant and unsymmetrically reversed. Moreover, the thin dark line constituting the reversal seemed to be nearly, or exactly in its proper place;[1] the obvious relative shift measured the lessened refrangibility of the emissive beam. In the gaseous envelope, then, of one and the same star we find a helium line originating at a low level moved towards the red, while its repetition by absorption higher up preserves its wave-length unchanged. The indicated difference in conditions can here scarcely be anything else than a decrease of pressure upward from the photospheric surface. The significance of such an inference hardly needs to be pointed out, and it seems impossible to avoid drawing it.

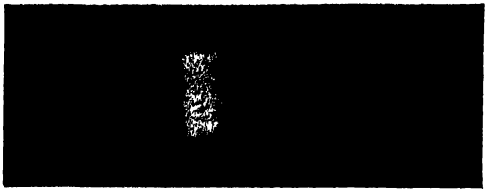
The red ray of hydrogen is particularly brilliant in $\beta$ Lyræ; but since it lies beyond the ordinary spectrographic range it has of late received little attention. Yet the history of the modifications which it assuredly undergoes, and of the modes of their correlation with those of its associates in the spectrum, must be learned, unless knowledge of this wonderful star is to remain essentially incomplete.

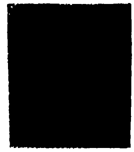
We may now endeavour to sum up our conclusions regarding its nature, tentative and fragmentary though they be. A

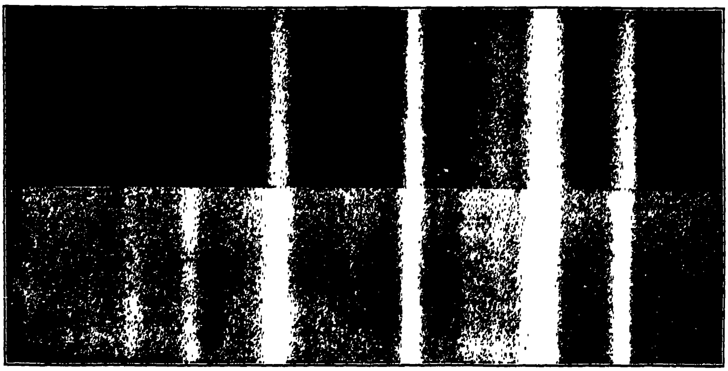
[1] *Astr. and Astrophysics*, vol. xii. p. 356.

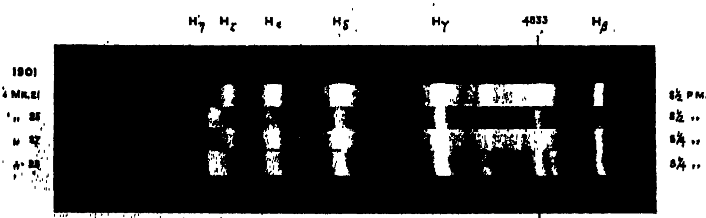
1. 

1a. 

2. 

3. 

4. 


5. 


THE ALTERNATING SPECTRUM OF NOVA PERSEI
STONYHURST COLLEGE OBSERVATORY.

1. Hζ Line in Spectrum of β Lyræ at Secondary Minimum.
1a. Hζ Line in Spectrum of β Lyræ at Second Maximum.
2. D-Lines in β Lyræ (Keeler).
3. D-Lines in Nova Persei (Hale).
4. Spectra of Nova Sagittarii.
5. Alternating Spectrum of Nova Persei (Sidgreaves).

finished theory on the subject cannot at present be formulated; but the ground may be prepared for it by the removal of inadmissible hypotheses and by the clarification of thought.

(1) The system of $\beta$ Lyræ is binary. Two stars, and no more, are concerned in producing the observed changes in the quantity and quality of its light. Both show strong hydrogen and helium absorption; one is distinguished besides by oxygen absorption, and it is this latter which, in all probability, emits the more conspicuous set of bright lines. There are indications, too, that a second set is occasionally sub-apparent, and that the spectrum really consists of two separate ranges of dark, and two accompanying ranges of vivid rays.

(2) The dark lines are in their normal positions at minima; they are shifted from them at maxima, when some of their number open out into doublets. The conjunctions at times of least light, and elongations at intervening epochs, of two bodies giving absorption spectra are thus presumably signified.

(3) At chief minimum, the more prominent bright lines are shifted towards the red, so as to lie beside the corresponding dark lines. The spectrum has then the coupled aspect distinctive of "Novæ" and of certain other emission-stars. The change of refrangibility during this phase cannot be due to motion; it may be due to pressure.

(4) During the second half of the period, reversals are a leading feature of the spectrum, which thus affords evidence, not only of orbital revolution, but also of a course of physical vicissitudes comprised in the same cycle.

(5) Finally, the cause of variability has to be considered. Is it to be found in mutual occultations? The geometrical conditions are such as to admit of an affirmative reply; the physical conditions are adverse. They involve a rarefaction of the circling bodies so extreme as to repel assent unless under the stress of rigid demonstration. And that is by no means at hand. Evidence on the subject could perhaps more easily be collected from objects with analogous light-curves, than from $\beta$ Lyræ itself. The endless complications which embarrass research in the "problem star" would not, for instance, be likely to present themselves in *d* Serpentis. Another variable, highly desirable to be included in such a comparative study, is R Sagittæ. This remarkable object has a period of seventy

days, symmetrically divided by two unequal minima, and two slightly disparate maxima. The light-curve, however, underwent a curious change in 1874. A reversal of the minima was perceived.[1] Equalisation first took place. Then the secondary minimum gradually gained emphasis at the expense of the primary; and the exchange of relative values was not redressed until 1883, when the pristine state was restored. An arrested tendency towards such a transformation is sometimes shown by $\beta$ Lyræ in the fluctuating accentuation of its subordinate phase, but it has never reached so far as a bisection of the period. A suggestion is, nevertheless, irresistibly conveyed that the two stars form similarly constructed systems. When the spectra of R Sagittæ, $d$ Serpentis, and U Pegasi have been examined, and their changes tabulated and collated, we shall be in a better position to interpret those manifest in the Lyre variable.

[1] Baxendell, *Proc. Manchester Phil. Society*, vol. xxiv. p. 14.

# CHAPTER XXII.

## STARS VARIABLE IN LONG PERIODS.

"LONG periods" of variability range from 120 to 610 days. None more protracted have been definitely ascertained, and those that are shorter belong, with rare exceptions, to stars differently characterised. The distribution of the

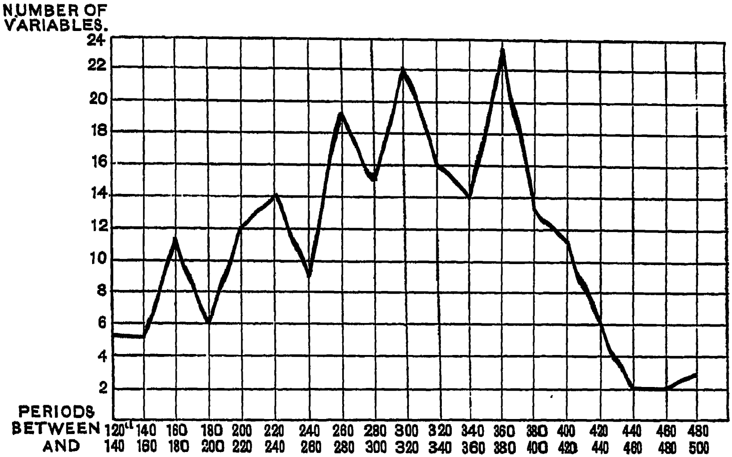



FIG. 31.—Distribution of the Periods of 208 Variable Stars.

periods we are at present concerned with is exhibited graphically in Fig. 31. They number 208, and are taken from Chandler's *Third Catalogue*, only three, which exceed 500 days, being for convenience omitted. Periods of several years have besides been ascribed to a few stars, but on insufficient grounds. No true conformity to them is maintained. Phases that are unusually slow are also

extremely uncertain in development. So far, the 610-day cycle of S Cassiopeiæ is the longest that can be depended upon to recur. A cursory reference to our diagram will show how largely, among long periods, those between 280 and 300 days preponderate. Accidents of discovery connected with the length of the year cannot well have produced this preference, which seems to be genuine, and not merely apparent. On the other hand, the indentations of the curve are assuredly casual, and will be smoothed down with the multiplication of objects.

The typical long-period variable is Mira Ceti. It was the first detected; it rises to the brightest maxima; it presents the most vivid and distinctive spectrum. More than 300 of its cycles have been watched, more or less attentively; yet familiarity has not diminished wonder at the "Wonderful" star.[1] Its modes of procedure are as much an enigma to the spectroscopists of Lick and Potsdam as they were to Fabricius and Holwarda. An instructive comment upon them is the omission, from Chandler's *Third Catalogue*, of the modifying terms appended to the mean period of 332 days in his *Second*. It amounts to an abandonment of the attempt to predict, with even approximate accuracy, the capricious changes of the Frisian pastor's *Stella insolita*. Argelander's laborious efforts for their regulation have thus proved futile. He considered an oscillation extending over 80 years, and comprising 88 periods, to be fairly well established, and found indications of another of 160 years;[2] but their supposed effects have ceased to be apparent. Guthnick's "long inequality," covering 200 cycles, will doubtless prove equally illusory. No method is indeed securely traceable in the accelerations or retardations of the maxima, and they digress to the extent of fully two months. Long and short periods can neither be perceived to alternate nor to occur in series; still opposite deviations balance each other; there is no progressive alteration in the length of the cycle.

The highest maximum and the lowest minimum recorded for Mira were both observed by Sir William Herschel. He found the variable nearly equal to Aldebaran on 6th November 1779,[3] while four years later it was invisible with a tele-

[1] Flanery, *Knowledge*, vol. xix. p. 230.

[2] *Bonner Beob.* Bd. vii. Th. ii. p. 332.

[3] *Phil. Trans.* vol. lxx. p. 342.

scope showing stars of the tenth magnitude. Of late it has not been known to descend below 9·5, and it sometimes stops short at 8·0 magnitude. Its greatest brightness is even more inconstant. No more than 5·6 magnitude was attained in November 1868,[1] or one-fortieth the lustre of the phase viewed by the Bath organist, and maxima higher than the third magnitude are uncommon. The course of change likewise fluctuates, but in general the rise is considerably more rapid than the decline, and the high-level status is maintained for about two months, the low-level for at least three, without striking alterations. Yet change is always in progress. The light-curve has no flat stretches.[2] No connection is apparent between the acuteness of the light crises in this star and the times of their occurrence.[3] They do not tend to become abortive when hurried, nor is delay accompanied by intensification. Argelander entirely failed to correlate irregularities of period with discrepancies in the amplitude of change. As the fruit of tercentennial experience it has, however, been learned that long-period variables are no transitory phenomena. Mira, at any rate, exhibits no symptoms of decadence since the maximum which surprised Fabricius in August 1596.

Its spectrum gives evidence of powerful disturbance, but none of duplicity. Motion-shifts depending upon orbital revolution are imperceptible. The periodicity of the star must be explained otherwise than by attributing to it a binary character. The task of doing so is indeed most arduous. Once in eleven months the brightness augments some hundreds of times, and concomitant spectral modifications afford assurance that these annual outbursts are accompanied by atmospheric ignition. What occasions them? We are ignorant; yet the issue may be narrowed by the following consideration. If external action of any kind were concerned in their production we should expect the incandescence to be coronal or chromospheric—to affect primarily the outer layers of the gaseous envelope. But in fact the innermost strata are those set aglow, while the overlying vapours remain comparatively

[1] Schmidt, quoted by Schönfeld, *Mannheimer Jahresbericht*, Bd. xl. p. 74.

[2] Nijland, *Astr. Nach.* No. 3733.

[3] Guthnick (*Astr. Nach.* No. 3745) holds that the star rises to exceptionally high maxima once in 59½ years. As the Italian proverb says, *Chi vivrà, vedrà.*

cool. The masking of a bright hydrogen line by calcium absorption places the subsistence of this relation beyond question. So far, then, the evidence favours the view that variability of the Mira type arises spontaneously, rather than through outside influence.

On the 13th of December 1885 Mr. J. E. Gore was struck with an unfamiliar reddish star of the sixth magnitude in the Club of Orion. No map included it, and until it reappeared a year later after an interval of quasi-extinction, there was no telling whether it should be reckoned as a Nova or a variable. Dr. Copeland recorded for it "a very beautiful banded spectrum of the third type, seven dark bands being readily distinguished with the prism." The intervening spaces appeared "full of bright lines, especially in the green and blue." Two of these were certainly emitted by hydrogen, and others probably by helium, since a vivid $D_3$ was observed by Von Konkoly ten days later, the adjacent sodium pair being, as usual, dark. Fig. 32 exhibits the light-curve of U Orionis during the maximum half of its period, as delineated by M. Porro at Turin 1889-90. Its form is by no means invariable. In general, the brightest phase is reached much more abruptly than it was in 1890. The main rise, however, is always prompt, and the decline gradual, although the minima appear to be well defined. They have not, indeed, owing to their faintness, been much observed. The widest amplitude of the star's change is from 5·3 to about 12·5 magnitude; but these limits are seldom attained. Nor is the assigned period of 375 days conformed to with any exactitude. As in the case of Mira, prediction has to be qualified with a large allowance for unexplained disturbance.

At high maxima $\chi$ Cygni radiates about 6500 times more powerfully than at low minima. The star, that is to say, has a range of fully nine and a half magnitudes, from the fourth to near the fourteenth. But in some of its cycles it fails to ascend beyond 6·5 magnitude; for it resembles the other stars of this class in having no fixed measure of change.[1] Its period is now 406 days; it has lengthened, on an average, by a quarter of an hour at each recurrence since Kirch, in July 1686, missed from its wonted place the star located by Bayer

[1] *Berliner Jahrbuch*, 1841, p. 93 (Olbers).

*in collo Cygni*;[1] nor is there yet any sure sign of a com-

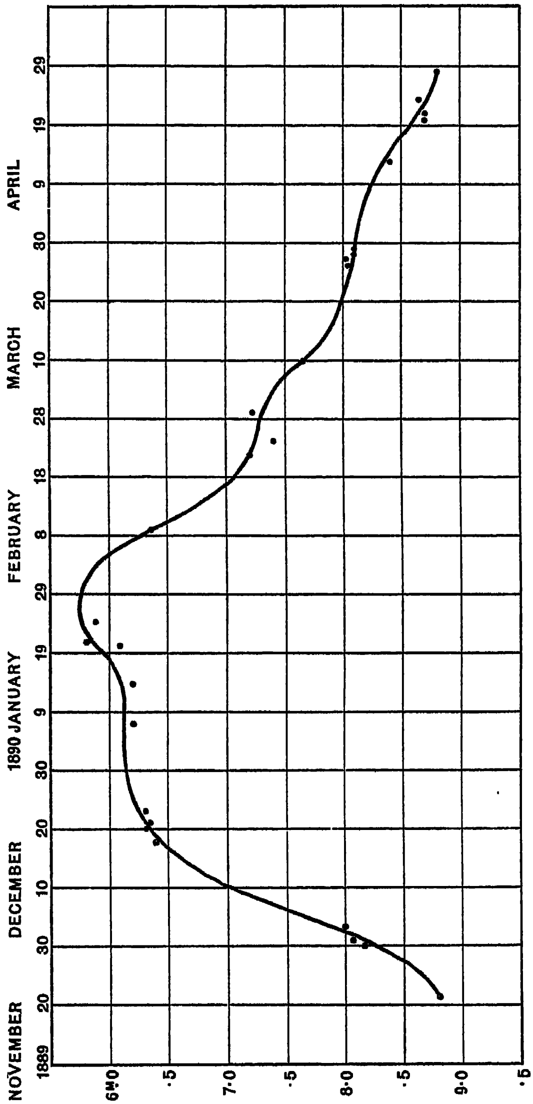



FIG. 82.—Light-Curve of U Orionis (Porro).

pensatory reversal. The nature of the secular perturbation thus betrayed can scarcely be imagined. Argelander noticed

[1] *Miscellanca Berolinensia*, t. i. p. 208.

besides deviations from the mean period up to forty days, and sought, with imperfect success, to analyse and regularise the inequalities upon which they depended.[1] The increase of light in this variable occupies 171 days, or considerably less than half the period. Its most brilliant phases are brief, while fainter maxima are sometimes prolonged for a couple of months. In 1847 the star remained visible to the naked eye during 97 days, although the usual time of "lucidity" is, by Argelander's estimate, only 52 days.[2] The scarlet blaze of its light is often very striking.

R Hydræ is an accelerating variable. In 1708 the interval from one maximum to the next was 500 days; it had shortened to 437 in 1870, and to 425 in 1891. The highest maxima are of 3·5 magnitude, the lowest more than six times less bright. The minima, on the other hand, occur with fair uniformity at 9·7 magnitude. Strongly red in all its phases, R Hydræ displays a gorgeous colonnaded spectrum lit up with bright hydrogen lines.

The variability of $L_2$ Puppis was discovered by Gould at Cordoba in 1872. The range in magnitude—3·5 to 6·3—is moderate, the period—137 days—comparatively short. Wide departures from it, however, are not infrequent, and it is almost equally divided between the ebb and the flow of luminosity.[3] The colour of this star suggests a conflagration, and its spectrum resembles and is no less effective than that of Mira.[4] An exceptionally large proper motion, for a member of its class, has been determined for it by Professor Porter of Cincinnati.

An analogous object is met with in W Puppis. Here the rise occupies 62 days, the decline only 58, the visual limits of variation being the eighth and eleventh,[5] the photographic, the ninth and twelfth magnitudes. The discrepancy is naturally accounted for by the non-actinic quality of light conspicuously red to the eye. The detection of bright hydrogen lines in a third-type spectrum gave Mrs. Fleming in 1895 [6] the clue to the character of this star. The fluctua-

[1] *Bonner Beob.* Bd. vii. p. 340.

[2] Humboldt's *Cosmos* (Otté's trans.), vol. iii. p. 236.

[3] Roberts, *Astr. Journ.* Nos. 295, 491-2.

[4] A. J. Cannon, *Harvard Annals*, vol. xxviii. p. 189.

[5] Roberts, *Astr. Journ.* No. 462.

[6] *Astroph. Journ.* vol. ii. p. 198.

tions inferred to take place from that unfailing symptom were looked for and quickly found. The light-curve of W Puppis is very regular, and takes a much sharper bend at minimum than at maximum.

In S Ursæ Majoris we meet a much older acquaintance. Its periodicity, discovered by Pogson in 1853, was established by a record of its magnitude made by Lalande in 1790. It is of a highly perturbed nature. The maximum brightness varies between 6·7 and 8·2 magnitude; the minima are uncertain to the extent of perhaps three magnitudes, some unusually faint at 13·3 magnitude having been watched by Baxendell. The actual length of the cycle is about 226 days; it is modified by a recurring inequality with a range of nearly eight days, but much more extensively by irregular deviations. These seem to be connected with two curious inflections of the light-curve. About six weeks before maximum the rise is arrested, sometimes for a few days, sometimes for as many weeks. A corresponding stay in the decrease of light usually precedes each minimum.[1] Upon the duration of these halts evidently depends the retarded or hurried accomplishment of the phases. Noteworthy besides is the occasional equalisation of the times occupied in waxing and waning. This is apparently a consequence of the partial abolition in certain cycles of the pause before minimum. That of 1875 was distinguished by a steady maximum lasting from 23rd February to 13th April, and followed by a decrease quicker than the preceding increase.[2] Similarly, the late Sir Cuthbert Peek's diagram for 1894 (copied in Fig. 33) shows a flat maximum antecedent to a precipitate decline. Again, four years later, the light during two months scarcely varied from the eighth magnitude;[3] and it may be remarked that, as in the sun, long maxima are low maxima. The mean light-curve of S Ursæ, from observations made at Harvard College, 1889-99, is depicted in Fig. 34. Only the general course of change can be followed by its means; the effects of temporary obstructions or disturbances are necessarily eliminated.

[1] Baxendell, *Journ. Liverpool Astr. Soc.* vol. iii. p. 52.

[2] Schönfeld, *Astr. Nach.* No. 2066.

[3] Peek, *Journ. Brit. Astr. Assoc.* vol. ix. p. 261.

Deep red, and often hazy when faint, this star has been seen nearly white at maximum—a not uncommon kind of colour-fluctuation. It gives a poorly-developed spectrum of the third type.

T Ursæ Majoris has a total range of nearly six magnitudes, and a period of 302 days; but its variations make no approach to uniformity. The maximum brightness is largely uncertain; the minima are sometimes, though rarely, as low as 13·5 magnitude. The luminous tide flows, at certain epochs, with extreme rapidity. Between 5th January and

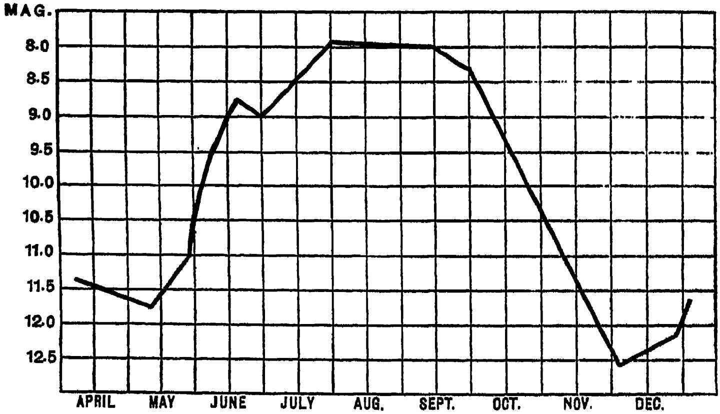



FIG. 33.—Light-Curve of S Ursæ Majoris in 1894 (Peek).

22nd February 1901, for instance, the star increased from 12·4 to 7·7 magnitude. In forty-six days it acquired a seventy-six-fold brilliancy, and the augmentation was accompanied by a blanching of its rays. Of their dull ruddy hue scarcely a tinge survived at full light. Fig. 35 reproduces the mean curve drawn at Harvard, which is, of course, much more symmetrical than any of the individual curves serving as its basis. The maxima and the minima appear from it to be about equally sharp.

The curve of T Cassiopeiæ, on the other hand, cannot be smoothed into shapeliness. It is represented in Fig. 36. The secondary maximum occasioning the hump on the upward branch is never absent, and protracts the cycle to 445 days, considerably more than half of which (240 days) are occupied

by the abnormally impeded phase of increase. The period is affected by a compensatory inequality.

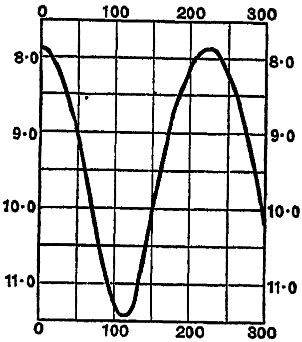



FIG. 34.—Mean Light-Curve of S Ursæ Majoris (Pickering).

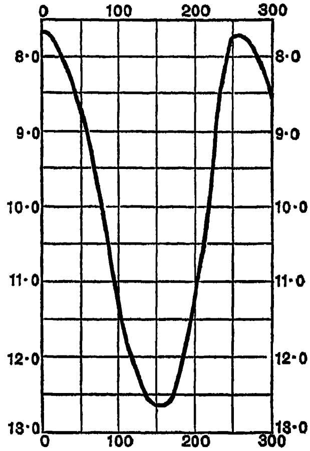



FIG. 35.—Mean Light-Curve of T Ursæ Majoris (Pickering).

The variability of R Leonis was detected by Koch in 1782; yet six score years of scrutiny have only sufficed to render more manifest the almost hopeless intricacy of the laws

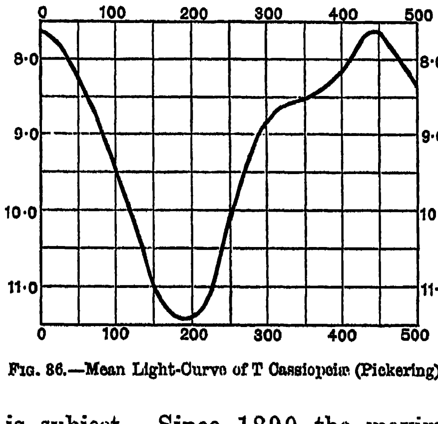



FIG. 36.—Mean Light-Curve of T Cassiopeiæ (Pickering).

to which it is subject. Since 1890 the maxima have been persistently accelerated, computations, founded on a nominal period of 312 days, being left in the lurch in November 1896 by forty-three days. That there is a large periodic

inequality admits of no doubt; "but the observations of the last few years," Dr. Chandler remarked in 1896, "show that it is complicated with other unknown terms," the neglect of which, pending the development of their nature, seemed to him safer than the attempt to use them for purposes of prediction in ignorance of their value. That is to say, the phases can be registered as they occur, but defy accurate anticipation. The glowing colour and brilliant spectrum of the star make it an object of singular beauty and interest. Its total range is from 5·2 to 10 magnitude, but the oscillations are often of less amplitude.

The variability of V Delphini was discovered by Mrs. Fleming in 1891 by the shining of bright hydrogen lines amid the flutings of its spectrum.[1] It is of enormous extent. Between maximum and minimum-light there is a difference of close upon ten magnitudes. Observed as of 7·5 magnitude on 1st October 1899 with the forty-inch Yerkes refractor, the star had on the ensuing 20th July sunk to invisibility, and must therefore have been below the seventeenth magnitude.[2] The period is 540 days.

A strange anomaly in the light-change of R Lyncis was placed on record at Sir Cuthbert Peek's observatory in 1898.[3] From a smouldering minimum the star had risen by 2nd March to 10·6 magnitude; when, suddenly reversing its course, it dropped in eighteen days to the thirteenth magnitude, but finally resumed the interrupted process of brightening, and mounted at the customary rate to a maximum of 7·5 magnitude on 11th August. Such apparent caprices constitute indeed a baffling enigma, but should, for that reason, be the more steadily kept in view in dealing with the general question of stellar variability. The high and low phases of R Lyncis are alike definitely marked. The period assigned to them is 380 days.

The variation of R Cygni exceeds eight magnitudes. In rising from one extreme to the opposite it gains a 2500-fold increase of light. The maxima, however, as usual in this class of variables, are very unequal, some being seven times

[1] *Astr. Nach.* No. 3025; Hartwig, *ibid.* Nos. 3211, 3596.

[2] Hale, *Yerkes Observatory Bulletin*, No. 18.

[3] *Journ. Brit. Astr. Assoc.* vol. ix. p. 260.

more brilliant than others. Mr. Espin believed in 1888 that a regular alternation of high and low phases might be counted upon;[1] but their subsequent disordered succession belied the inference. The star is among those in which dimness is occasionally attended by a curious diffuseness of aspect. Thus in February and March 1894, having previously sunk out of sight with a 6⅓-inch refractor, it came again into view, at the Rousdon Observatory, in the shape of a small bluish nebula, resembling a faint comet.[2] This object, which had contracted on 24th March into a needle-point of light of the

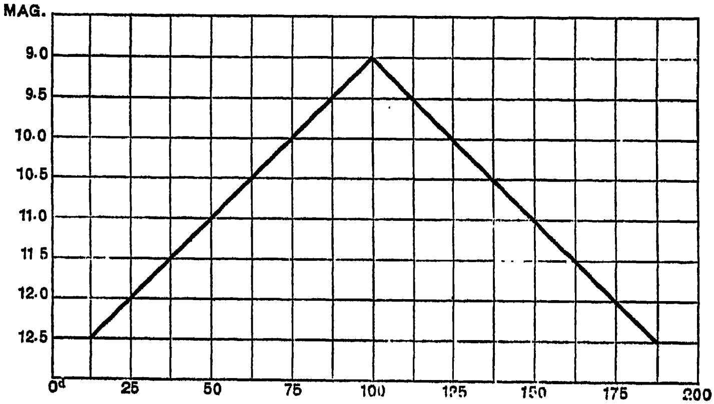



FIG. 37.—Light-Curve of T Andromedæ (Pickering).

twelfth magnitude, resumed its nebular appearance in February 1895 and March 1896. The mean period of R Cygni is 426 days; but the interval between the maxima of November 1890 and February 1892 amounted to 457.[3] No more than 150 days are, as a rule, spent in the rise.

The unique form of light-curve represented in Fig. 37 is assigned by Professor Pickering to T Andromedæ. Derived from photographic data, it awaits visual confirmation, yet can scarcely be widely erroneous.[4] The uniform progression it depicts need not, indeed, be accepted as a rigid reality; it must be encroached upon by sundry kinds of disturbance, and

[1] *Astr. Nach.* No. 2859. [2] Peek, *Variable Star Notes*, No. 4.
[3] Townley, *Publ. Washburn Observatory*, vol. vi. pt. iii. p. 60.
[4] *Astroph. Journ.* vol. i. p. 305.

the maxima, however brief, cannot be instantaneous; at every full tide there is an interval of "slack water." Nevertheless, if even the mean curve prove to be linear, the circumstance will be of great interest, and the star, meanwhile, merits close attention. Owing to its redness the photographic curve is transposed downward on the scale to the extent of one and a half magnitudes,[1] so that the variable shows four times brighter to the eye than to the sensitive plate. Hence changes of colour, should they at any time supervene, would necessarily produce large distortions in the automatically registered course of light-fluctuation. The systematic comparison of visual and photographic determinations of magnitude might, indeed, be used as an effectual means of testing the permanence in hue of long-period variables. While it remained constant, the curves of light-change, obtained retinally and chemically, should flow parallel to one another; they would merge together if the star blanched, and diverge still farther if it reddened. The variability of T Andromedæ was discovered by Dr. Anderson of Edinburgh in 1893. The period seems to have suddenly shortened from 281 to 265 days in 1895.

Variables of the fourth spectral type are mostly crimson-tinted, and have protracted periods. Indeed, these two characteristics show some kind of mutual dependence,[2] Chandler's rule, "the redder the star the longer the period," being, on the whole, conformed to. Apposite examples are furnished by S Cephei, U and V Cygni. The period of S Cephei averages 484 days, but is subject to an alternate lengthening and shortening.[3] More than half of it, or about 257 days, is occupied in the ascent from minimum to maximum, and this exceptional arrangement is consistently maintained. The light-curve is highly irregular. Smoothed out by striking a decennial balance, it took the form shown in Fig. 38 from the Harvard College representation. But its dissymmetry is greatly modified from that of the tracing given by the observations of any single period. Usually there is a rather swift increase and decrease, followed by intervals of

[1] Parkhurst, *Popular Astronomy*, vol. i. p. 462.
[2] Schmidt, *Astr. Nach.* No. 1897; Chandler, *Astr. Journ.* Nos. 186, 193.
[3] Parkhurst, *Pop. Astr.* vol. i. p. 266.

approximate constancy, at maximum, of about a hundred, at minimum, of fifty days.[1] Not unfrequently, however, the curve has a sharp apex, and its downward flow is interrupted by a secondary rise. Such "stand-stills" (as Mr. Maxwell Reed calls them) are a familiar feature of long-period variability. Seventh-magnitude brightness is never fully attained by S Cephei, and it occasionally drops below the thirteenth magnitude. Like many very red stars, it has accesses of bad definition. They occur, very remarkably, not at low light, but

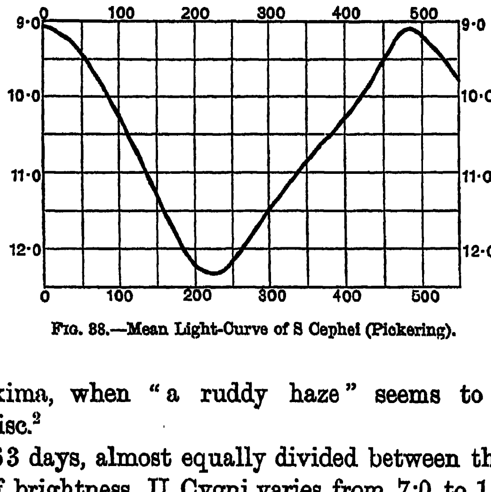



FIG. 88.—Mean Light-Curve of S Cephei (Pickering).

near maxima, when "a ruddy haze" seems to envelop a definite disc.[2]

In 463 days, almost equally divided between the gain and the loss of brightness, U Cygni varies from 7·0 to 11·6 magnitude; yet with no approach to regularity. The maxima are sometimes fainter than the eighth magnitude; the minima fluctuate, it is thought cyclically,[3] from 9·4 to 11·6 magnitude. The periodicity, too, is complicated by an outstanding disturbance.

The period of V Cygni is 418 days, and the rise, which occupies 220 days, is disproportionately slow. Lindemann registered a steady decline in the maximum-brightness of the star, from 6·8 magnitude in 1882 to 8·4 in 1891;[4] in some cycles it does not exceed 9·5 magnitude; while the minima occur, with tolerable uniformity, at the low level of

[1] Reed, *Astr. Journ.* No. 330.
[2] Peek, *Variable Star Notes*, No. 2, p. 18.
[3] Knott, *Observatory*, vol. xiii. p. 111.
[4] *Astr. Nach.* No. 3184.

13·5 magnitude. The maxima are succeeded, at intervals of two months, by subordinate phases of recovery. The colour of V Cygni is especially intense. The carmine of its beams corresponds to a powerful stoppage of the complementary blue and violet radiations, by which a splendid preponderance is secured to the red end of the spectrum. No bright lines have been certainly recognised in the dispersed light of either U or V Cygni; they are, as we have seen, prominent in U Hydræ, a fourth-type variable of no settled periodicity.

A fundamental distinction is apparent between the two chief kinds of stellar variability. Stars with "short" periods are—in a few cases demonstrably, in the rest presumably—close pairs, their mode of circulation prescribing, in some unknown way, their laws of light-change. The strict accuracy of its fulfilment hence results as if by mechanical constraint. Mira-variables, on the contrary, give no signs of duplicity; and the marked irregularity of their phases affirms their origin through a complex interaction of physical disturbances. That these are internal and constitutional, there is the best reason to believe. Spectroscopic symptoms are fairly decisive on the point. They have as yet, however, been very partially observed. A bare gleaning of facts has been gathered, and we want a full harvest as a foundation for safe inferences. A spectroscopic study throughout their cycles of variable carbon-stars would, for instance, be most valuable. The behaviour of the bright lines shown by them might even prove crucial, first, as regards the position in their atmospheres of the emitting strata, next, as to the seat of the recurring commotions. The spectra of U and V Cygni and of R Leporis may be cited as among those claiming systematic and prolonged observation.

The reality of the diffuse aspect intermittently presented by certain variables could readily be tested by examining them at such times with a reflector. Refractors, owing to their imperfect colour-correction, often produce abnormal images of objects peculiarly tinted. Nevertheless, if this were the true and only explanation of the effects in question, we should expect to find them develop under uniform conditions, and they appear instead incalculably, and as if by caprice. An instructive example is furnished by V Cygni. On 19th

July 1882, six weeks after a maximum, Lindemann[1] saw the variable at Pulkowa as an indistinct coppery disc. But at the same interval, *before* the high maximum of 31st August 1882, it showed not a trace of nebulosity, although intensely red. On 8th October 1883 it appeared almost blood-coloured and very diffuse, while nine days later its image was point-like, stellar, and precise. Analogous observations have been made by Mr. Grover, Sir Cuthbert Peek's assistant, on R, S, and T Cassiopeiæ, R and S Ursæ Majoris, and several other objects of their class; and by Mr. Knott on U Geminorum, which, as a white star giving a continuous spectrum, ought to come regularly to focus. For not a few stars, such as R Coronæ and S Herculis, dim, bluish nebulosities are substituted at low minima; and not uncommonly, even on nights of excellent definition, variables in moderately high phases appear sharp, though very red, and as if projected on a background of glowing haze. Then again, they present a clearly outlined disc, or a "large, woolly, ill-defined image resembling a small but bright planetary nebula."[2] Most of these diversities defy anticipation; they can be associated with no particular stages of variation, and some of the reddest stars, R Leonis and R Leporis among the number, appear to be exempt from them. Yet their literal interpretation as indicative of physical alterations in the bodies affected by them would lead to consequences of outrageous improbability. Provisionally, at any rate, the wiser course is to refer them to a combination of atmospheric and instrumental causes. With these, no doubt, a genuine change of luminous quality concurs, whereby semi-extinct stars, being thrown out of focus, assume a nebular disguise. It is noteworthy that the records of a series of observations on the minima of twenty-two long-period variables, executed with the Yerkes forty-inch refractor in 1900,[3] include no mention of unusual phenomena. Attention, however, seems to have been directed entirely to the determination of magnitudes, nor had any of the stars on the list (U Geminorum excepted) been previously remarked for optical peculiarities.

A clue to the labyrinth of stellar variations is likely to

[1] *Bulletin de l'Acad. Imp.* t. xxix. p. 302.
[2] Peek, *Knowledge*, vol. xv. p. 52.
[3] *Yerkes Observatory Bulletin*, No. 13.

be afforded by the continued investigation of solar periodicity. Comparisons of the spot-curve with the light-curves of Mira, $\chi$ Cygni, T Ursæ, or almost any of their congeners, bring a conviction that the phenomena differ in degree rather than in kind. The plottings of solar and stellar disturbances show the same character of dissymmetry, and the same order of irregularity. In both classes of representation, high summits are usually sharp, low summits blunt. In both, the course of change is now halting, now hurried. Hesitations, subordinate ascents, and subordinate subsidences before completing the phase, are common features. There is, indeed, no mode of departure from uniformity traceable in the solar cycle that cannot be strictly paralleled in the caprices of stellar emission. The analogy has been rounded out by the discovery that the sun, at spot-maxima, is essentially a bright-line star. Its spectrum then shares, in a just perceptible degree, the blazing quality that distinguishes the spectra of Mira-variables. This is a further and an irrefragable proof of the correspondence of the epochs. Light-maxima in the stars match spot-maxima in the sun. In each case a development of internal energy gives rise to enhanced incandescence, accompanied, in the single specimen of a sub-variable star within reach of detailed observation, by rendings of the photospheric envelope, and outbursts of chromospheric flames. Looking a little closer, we can discern the probability that the cyclical variations of all these bodies depend essentially upon a rise and fall of activity in the vertical circulation by which radiation is maintained. The rate of conveyance of heated matter from within outward must be a determining factor of photospheric brilliancy, transcendent lustre implying unusual celerity of transport. This is the vital process of suns, the checking of which must immediately become sensible in their diminished output of light. Here, if anywhere, will be found the secret of stellar variability.

# CHAPTER XXIII.

## PECULIAR AND IRREGULAR VARIABLES.

THE stars varying in periods comprised between thirty and a hundred days are not numerous, and they are often peculiar. Among them are to be found such remarkable objects as R Sagittæ, R Scuti, U Geminorum, and S[2] Cygni. Of R Sagittæ, with its double period and reversing minima, something has already been said. The possibility that it is in reality a "short-period variable" on a magnified time-scale is suggested by its resemblance to $\beta$ Lyræ, and emphasises the question as to its spectroscopic duplicity. Its irregularities, though considerable, do not appear to transcend the limit of what might be explicable in a gravitational system.

This, however, cannot be said of R Scuti; and since the two stars are analogous in their mode of variation, a rationale clearly impossible for one must be regarded, for that reason alone, as highly improbable for the other. The fluctuations of R Scuti, first observed by Edward Pigott in 1795, extend from 4·4 to about 9·7 magnitude, and have a nominal period of seventy-one days. But they cannot be even empirically embraced in any formula. As Mr. Flanery remarked in 1896, "No set of elements yet devised will fit this star long."[1] Each in turn has to be rejected as unserviceable. Thus, on 6th May 1897, the star showed a complete inversion of phase;[2] it was at a low minimum instead of at the computed maximum. It then rose to an unforeseen brightness of 5·4 on 11th June, diminished to half-light during eighteen days, and finally, remounting the slope it had just descended, shone duly at the predicted maximum of 17th July. Again, it varied less than a

[1] *Knowledge*, vol. xix. p. 230. [2] *Ibid.* vol. xx. p. 237.

magnitude for two months after the maximum of 29th August 1896, but underwent a precipitate decline at the end of the stationary spell. The light-curve, from Mr. Flanery's observations July to October 1895, is given in Fig. 39. It is that of a star which refuses to be bound by the shackles of any definite theory. Faint and brighter minima alternate, as Argelander long ago perceived; and they perhaps, now and again, exchange relative values, like those of R Sagittæ. If,

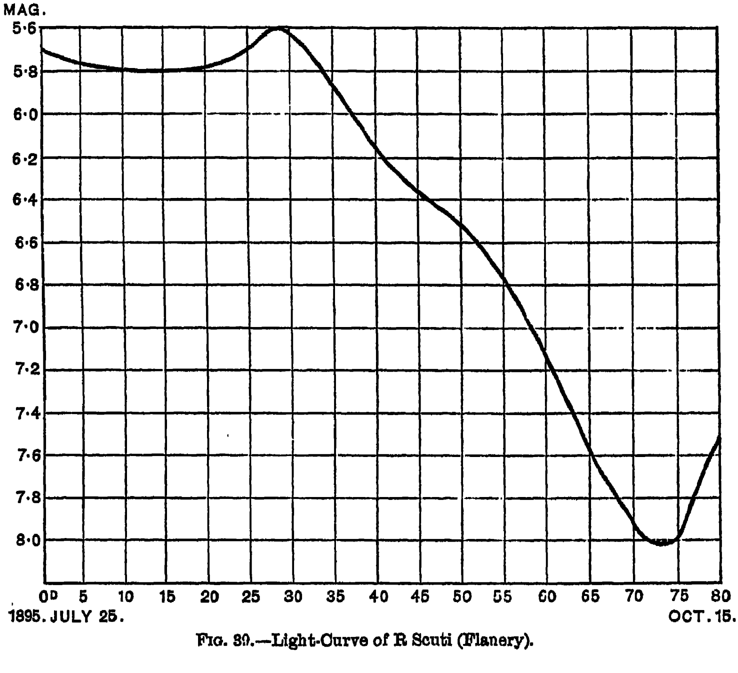



FIG. 39.—Light-Curve of R Scuti (Flanery).

then, we double the period, and call it 142 instead of 71 days, the star might rank, despite its vagaries, as an analogue of $\beta$ Lyræ and R Sagittæ. For a subordinate minimum, placed midway between two maxima, is a feature common to all three, though the other circumstances of variation are in each star widely different. Such resemblances in the midst of diversity are extremely perplexing to students of stellar light-change. The similarity of some of the phenomena suggests a uniform principle of explanation; but the attempt to extend its application serves only to undermine the credit it originally

possessed. The eclipse rationale, for example, suits $\beta$ Lyræ passably well, and might be accommodated to the less equable phases of R Sagittæ, but is wholly incompatible with the disordered fluctuations of R Scuti. This, however, in view of their fundamental resemblance to those of the accurately variable star in the Lyre, raises the question whether eclipses can be regarded as occurring in the one case, when they assuredly do not occur in the other. Over and over again this difficulty presents itself. No theory seems elastic enough to bear the strain put upon it by the variety of the facts. Each member of a group of related stars adds its quota to the burthen of explanation to be borne; until finally the breaking point is

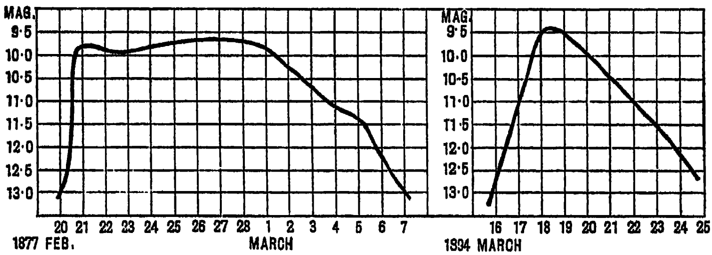



FIG. 40.—Long and Short Maxima of U Geminorum.

reached, and a collapse ensues, leaving the ground encumbered with the débris of the original speculation.

R Scuti might usefully be made the subject of detailed spectrographic investigation. Bright lines shine in the blue and violet sections of its light; but they have not been identified, and the flutings associated with them appear ill-pronounced, or even subject to effacement.

As a curiosity of the skies, R Scuti is much outdone by a small star in Gemini, the abnormal behaviour of which was noticed by Hind in 1855. Habitually tranquil at 13·1 magnitude, U Geminorum rises with amazing celerity to near the ninth once in two, three, or four months. A leap upward of nearly four magnitudes is often accomplished in a single day, and that without preliminary fluctuations. The descent is always much slower, but along a very changeable curve. Two types of maximum are shown in Fig. 40. In one, the

episode of brightening occupies fifteen to twenty days, in the other it is terminated in nine or ten. And, as a rule, they alternate one with the other. Nothing, indeed, is certain about this star except its uncertainty. "Predictions in regard to it," Mr. Parkhurst concludes from his experience, "can be better made after the fact."[1] The greatest light varies from 8·9 to 9·7 magnitude;[2] the least to a rather larger extent. Thus on 28th February and 26th March 1897 the star must have been below fourteenth magnitude, since Father Hagen lost sight of it with the twelve-inch refractor of the Georgetown College Observatory.[3] No relation is perceptible between the amount and the duration of change; long and short maxima are indifferently high and low. They are fickle, too, in their time-connections. The period—if it can be called a period—may be as short as 71, or as long as 126 days. Their unpunctuality apart, the changes undergone by U Geminorum bear a strong resemblance to those of cluster-variables. There are the same relatively prolonged intervals of repose, followed by vehement spasms of activity, beginning abruptly, dying out gradually. It will be of much interest to inquire whether the rays of objects so singularly and so similarly affected approximate to uniformity in quality. Those of U Geminorum are in colour dull bluish white; they give, according to Pickering and Copeland, an ordinary continuous spectrum. Still it is possible that peculiarities might be revealed by special scrutiny with powerful instruments.

U Geminorum ranked as a unique object until $S^2$ Cygni was discovered. Miss Louisa D. Wells in 1896 traced the fluctuations of the latter on the Harvard plates from 7·2 to below 11·2 magnitude; and the shortness of their apparent period of forty days combined so unusually with their wide range,[4] that they immediately became a cynosure for observers in that branch. The more closely they were watched, the more nearly they were found to conform to those of Hind's variable. In both stars, stationary minima are interrupted, at intervals not wholly irregular, by sudden ascents of three or four magnitudes; and as in U Geminorum, so in $S^2$ Cygni, long and short maxima are coupled together in pairs, yet by no invariable law.

[1] *Pop. Astr.* vol. v. p. 164.
[2] Yendell, *ibid.* p. 17.
[3] *Astr. Journ.* No. 400.
[4] Pickering, *Astroph. Journ.* vol. iv. p. 370.

Breaks in the alternate succession have been in each case recorded. In March and April 1897, for instance, $S^2$ Cygni rose to consecutive short maxima,[1] and a pair of long maxima again marred the rhythmical flow early in 1900. The curve for a double period is reproduced, from a drawing by Messrs. Parkhurst and Daniel, in Fig. 41. They comment on "the sharp turns in the curve at the beginning and end of maximum" as being "peculiar to this type of variable,"[2] which they judiciously assimilate to that prevalent in clusters. The mean period of about fifty-seven days attributed to $S^2$ Cygni has

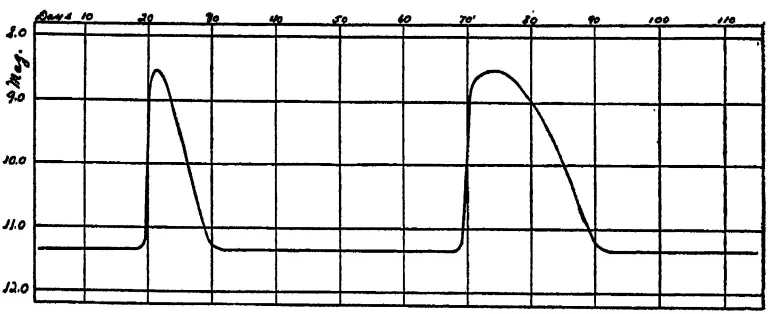



FIG. 41.—Light-Curve of S2 Cygni.

a wide margin of uncertainty. The interval from one maximum to the next may be curtailed to thirty-six, or expanded to sixty-three days, and that without traceable plan or method. Revolution in an orbit is hence absolutely excluded from among the possible causes of light-change. An hypothesis proposed by M. Hartwig of Bamberg[3] merely illustrates the baffling nature of the problem set by this star. He suggests that the maxima are occasioned by the brief kindling, at periastron passage, of a satellite pursuing a highly eccentric path. The irregularities of the period, he thinks, may be accounted for by a rapid gyration of the line of apsides. The blazing of "new" stars is, in his view, an analogous phenomenon;[4] but new stars exhaust their energy in a single display, while the variables in Gemini and Cygnus seem to have a limitless power of recupera-

[1] Parkhurst, *Pop. Astr.* July 1900, p. 343.
[2] *Astroph. Journ.* vol. xii. p. 268.
[3] *Vierteljahrsschrift Astr. Ges.* Jahrgang xxxiv. p. 315.
[4] *Astr. Nach.* No. 3553.

tion. The light of $S^2$ Cygni is tinged with blue; nothing has been published regarding its spectrum.

Although narrow in range (4·6 to 5·4 magnitude), the variations of *u* Herculis are unsurpassed in singularity. Recognised by Schmidt in 1872,[1] they have proved to be "irregularly periodic"; their tendency to preserve definite time-relations appears to be continually resisted and sometimes overborne by countervailing influences. Occasionally they conform approximately to a forty-day cycle, then break loose, and become for a time utterly lawless. The minima are attended by extraordinary fluctuations; the maxima are normally tranquil. The star was marked "red" in the Copenhagen Catalogue, but is now pale yellow, and shows a helium spectrum. Scant attention has of late been bestowed upon it.

A southern star noticed by Dr. A. W. Roberts[2] in 1891 to vary from 6·8 to 8·0 magnitude in a period of 38½ days, is remarkable for its phenomenally quick rise. Only 5½ days are needed for the tripling of its light, while thirty-three elapse during the corresponding subsidence. Hence, if the average ratio for Cepheid variables of the times of increase and decrease held good for U Carinæ, its period would at once be abridged to eighteen days, and there could be no mistake about its membership of a class to which it is affiliated by the type of its variations.

The periodicity of R Lyræ, detected by Baxendell in 1856, often much perturbed, is never wholly effaced. Argelander found it to be comprised within forty-eight days, which Schönfeld reduced to forty-six; yet in 1872 Schmidt considered it uncertain between the limits of thirty and sixty days.[3] Pannekoek's introduction of a periodic term for its regularisation[4] can be reckoned only a temporary expedient. The oscillation is of small amplitude, from 4·0 to 4·7 magnitude, but two striking outbursts of light, witnessed by Sawyer in November 1884,[5] imply essential instability. The simultaneous development of emission-rays might possibly have been observed had a prismatic eye-piece been at hand; but no spectroscopic

[1] *Astr. Nach.* Nos. 2075, 2420, 2491, 2492.
[2] *Astr. Journ.* Nos. 491, 492 (1901).
[3] *Astr. Nach.* No. 1905.
[4] *Journ. Brit. Astr. Assoc.* vol. v. p. 262.
[5] Pickering, *Proc. Amer. Acad.* vol. xii. p. 403.

examination was feasible at the critical moments. Ordinarily, the star, which is deeply tinted with orange, gives a superb colonnaded spectrum unmarked by bright lines.

Periodic cannot be sharply distinguished from irregular variables. Stars of an intermediate character are quite common. Some degree of precision in change may even be temporarily maintained by objects eventually found to be eminently unmethodical in their modes of procedure. Such are $\alpha$ Herculis, $\alpha$ Orionis, and $\beta$ Pegasi. Each assumed on first acquaintance a false air of submissiveness to a time-law, which each very soon laid aside. Their fluctuations rather exceed half a magnitude, and are included in an indeterminate number of months; their progress can in no wise be anticipated. Similarly, stars credited on historical grounds with extremely long periods have of late paid not the smallest regard to them. An instructive example is met with in R Cephei. Catalogued by Hevelius in the seventeenth century, and by Groombridge in 1807, as of the fifth magnitude,[1] it thereafter lost light, and in 1840 had sunk to the tenth magnitude. Collating all the available data, Pogson in 1856 assigned to the diminished star a period of seventy-three years, and predicted its restoration to naked-eye visibility in 1880.[2] But the prediction remains unfulfilled; the obscurity of R Cephei seems likely to be permanent.

At Potsdam in 1898 MM. Müller and Kempf noticed a star in Perseus[3] as variable in an unprecedented fashion.[4] After an indefinite term of constancy at 6·3 magnitude, it began in 1892 to decline at the very slow rate of one-eighth of a magnitude yearly, and continued to do so for six years. The counter-process was comparatively rapid. In twenty months the object had regained its former status, so that the complete oscillation occupied $7\frac{2}{3}$ years. This time, however, there was no long stationary maximum. Already by the end of 1899 fading had made some progress; but it remains to be seen whether any true periodicity can be established.

A period of five years, ascribed by Mr. Espin to 63 Cygni,

[1] Schönfeld, *Mannheimer Jahresberichte*, Bd. xl. p. 113.

[2] *Monthly Notices*, vol. xvii. p. 23.

[3] B.D. +30° 591, now known as X Persei.

[4] *Astr. Journ.* Nos. 434, 462; *Astr. Nach.* No. 3577.

has been rejected on further experience of fluctuations distinctively capricious. Many, perhaps most red stars, are unstable to the extent of half a magnitude; and 63 Cygni is a very red star. The fact that it is one and a half magnitudes fainter chemically than visually, supplies a kind of measure for the intensity of its colour.

The empirical rule that irregularity gains more and more the upper hand with increasing length of period [1] is illustrated by S Persei. Indeed the order of succession in the changes of this object is by no means satisfactorily ascertained. Safarik [2] and Hagen [3] hold them to be rudely periodical in about two and a third years; but most other observers prefer to consider them as entirely irregular.[4] Their range though wide, from near the seventh to the thirteenth magnitude, is seldom completely traversed. Experience alone can decide whether the rudimentary method traceable in these variations during fourteen years previous to 1894 will continue to regulate them in the future. Phases so unpunctual are liable to effacement. Quite possibly, the actual instability of S Persei represents a more or less transitory state, which may be succeeded by one of approximate constancy in shining.

The most illustrious of casually variable stars is $\eta$ Carinæ, formerly designated $\eta$ Argûs. Futile attempts have been made to accommodate it with periods. It has none. It is, in the full sense of the term, irregular. Its changes are perhaps modified by influences of an unimaginable nature connected with the vast surrounding nebula. But those influences undoubtedly act upon a body of inherently peculiar constitution. The spectrum of $\eta$ Carinæ is of a kind associated in every other known instance with absolute whiteness. It resembles that of P Cygni;[5] many hydrogen and helium lines are brightened in it, yet the star shows the colour of a Mira-variable. Whether this was always so or not, we have no means of deciding. The first note of a distinctive hue in the southern wonder-star

[1] Safarik, *Journ. Brit. Astr. Assoc.* vol. ii. p. 293.

[2] *Astr. Nach.* No. 3011. [3] *Astr. Journ.* No. 231.

[4] Peek, *Journ. Brit. Astr. Assoc.* vols. ix. p. 260; x. p. 156.

[5] Miss Cannon found indications, in the spectrum of $\eta$ Carinæ, of a composite origin from a solar, and a bright-line helium star. *Harvard Annals*, vol. xxviii. p. 175. Sir David Gill recorded numerous spectral coincidences between the southern variable and Nova Aurigæ. *Monthly Notices*, vol. lxi. p. 456.

was made by Piazzi Smyth, 1st January 1845, when he announced from the Cape a fresh increase in its light. For a month back, he wrote, it had been brighter than Canopus, and very red.[1] Then in 1850 Gilliss found it to outmatch Mars in depth of tint; and Thome described it in 1887 as of a "dull scarlet," passing into "bright orange" during a slight temporary rise. The history of this star is familiar to most of our readers.[2] It need not here be repeated. One fact in addition to those currently stated may, however, be mentioned. In his star-maps of 1603, Bayer marked $\eta$ Argûs as of the second magnitude, probably on the authority of Petrus Theodorus of Embden, who navigated the Indian seas 1594 to 1596. The variable was then equally bright in the sixteenth and in the eighteenth centuries, and its comparative insignificance when Halley placed it in the fourth rank was due to a merely transient decline. Whether the splendour of its beams has ever before been so completely shorn away as it is now, might be questioned. Excesses entail exhaustion, and the flaring maximum which culminated in 1843 was followed by a re-active sinking towards the ashes of extinction. Since 1886, as the observations of Finlay, Innes, and Roberts testify, the star has wavered between 7·0 and 7·7 magnitude, and no sign of its speedy restitution to brilliancy is perceptible. Its future is beyond divination. The present minimum may be indefinitely prolonged, but further change is more likely in the case of so ruddy an object. Another great outburst cannot indeed be reckoned upon even for a remote age. A "temporary" character may so far belong to $\eta$ Carinæ that its biography will include but one absolute maximum. The star is sensibly devoid of proper motion.[3] Its distance from the earth must accordingly be prodigious.

The capricious disappearances of R Coronæ surprised Pigott in 1795. Usually of about the sixth magnitude, the star is liable at any moment, without note of warning, to drop to the thirteenth. The intervals of maximum lustre sometimes last for years. One extended from 1817 to 1824, another from 1843 to 1845.[4] But in the last-named year, and again in

[1] *Monthly Notices*, vol. vi. p. 244. [2] *System of the Stars*, p. 116.
[3] Roberts, *Astr. Journ.* No. 492, p. 89.
[4] *Astr. Nach.* Nos. 624, 796, 806.

1852, R Coronæ vanished from view with Argelander's comet-seeker, regaining brightness on each occasion slowly, and, as it were, with difficulty. Of late its descents have been less profound. Schmidt observed a minimum at twelfth magnitude in August 1883;[1] Sawyer recorded on 13th October 1885 one arrested at 7·4 magnitude.[2] Having been visible to the naked eye nearly throughout 1893, the star sank to the ninth magnitude about 7th March 1894, and after an intermediate partial recovery, to 10·25 on 1st August.[3] By the end of the year the phase of instability seemed to have terminated. These lawless fluctuations, taken in connection with the extraordinary spectral changes ascribed to it, render this object one exceptionally inviting to careful study.

An analogue to it, but with a much narrower range of mutability, is the lucid white star $\epsilon$ Aurigæ. Ordinarily of the third magnitude, it fades at long and uncertain intervals to one-quarter of this brightness. One such diminution was observed by Heis in 1847; another by Schmidt in 1875.[4] There is nothing in the quality of the light to account for them. The spectrum is modelled on that of Procyon, only with an increase of definiteness, and marked differences of relative intensity in the lines.[5]

The vicissitudes of T Tauri derive special interest from their presumable connection with those of a group of nebulæ. Discovered by Hind 11th October 1852, it dwindled during fifteen years from tenth to twelfth magnitude *pari passu* with the fading of the adjacent "temporary" nebula, but attained in March 1868 a second and higher maximum, coincidently with the brightening of "Struve's nebula," another member of the collection. Again it declined, and was left unnoticed from 1877 until Burnham and Barnard, directing the Lick thirty-six inch to its place in October 1890, perceived it as the faint nucleus of a small condensed nebula,[6] which four and a half years later survived only as a feeble glow round the almost extinct variable. The glow was resolved by the Yerkes refractor into a little wisp of nebu-

[1] Gore, *Revised Cat. of Var. Stars*, 1888. [2] *Astr. Journ.* No. 151.
[3] H. Corder, *Memoirs Brit. Astr. Assoc.* vol. v. pt. ii. p. 32.
[4] *Astr. Nach.* No. 2704.
[5] A. C. Maury, *Harvard Annals*, vol. xxviii. p. 31.
[6] *Monthly Notices*, vols. l. p. 94; lv. p. 445.

losity, attached brush-wise to the star;[1] and partial impressions of it came out on plates exposed by Professor Keeler for four hours with the Crossley reflector, 6th and 29th December 1899.[2] "Can it be," Professor Barnard asks in surprise, "that the star becomes essentially a nebula as it sinks in light?" The question goes to the root of cosmic relations, and it is raised under more than one aspect by investigations of stellar variability. The associations and transformations of T Tauri are hence of profound significance, and should be diligently supervised until they can be linked together by some rational principle of causation.

Irregular variability has a wide and indefinite reach. It includes changes almost instantaneous, and changes well-nigh millennial in their development. The light of certain stars has undergone a slow secular decline. A noteworthy instance is that of $\theta$ Eridani, identical, as Dr. Anderson has conclusively shown,[3] with Ptolemy's "Last in the River" (the Arabic *Achernar*), the title and honour of which have been usurped by the more southerly, and now far brighter $\alpha$ Eridani. Al-Sûfi in the tenth century reckoned $\theta$ among the thirteen brightest stars visible in Irak; and it was still of the first magnitude in 1437, the epoch of Ulugh Beigh's Catalogue. Yet it had sunk to the third when Halley visited St. Helena in 1677, and of the third it still remains. Two other stars which have undeniably faded with the lapse of centuries are $\beta$ Leonis and $\delta$ Ursæ Majoris,[4] and their fading may even now be imperceptibly progressing. Nor is their eventual restoration by any means assured. Accessions of lustre are rarer, and often transitory. On 6th August 1868, 83 Ursæ Majoris, a sixth-magnitude star near Mizar, was seen by Birmingham to be the equal of $\delta$ Ursæ; though for that night only. The next, it had visibly gone off, and before long the whole of its added splendour had departed. Its amount was very considerable. The star attained, during its unexplained rise, to threefold its customary brilliancy. One of Burnham's close pairs, $z$ Virginis, underwent in 1866 a similar phase. This was before it was known to be double, so that our curiosity as to whether both the nearly equal components shared in the

[1] *Monthly Notices*, vol. lix. p. 374.
[2] *Ibid.* vol. lx. p. 425.
[3] *Knowledge*, vol. xvi. p. 124.
[4] Gore, *ibid.* vol. xxii. p. 176.

brightening remains ungratified. Red stars not infrequently drop abruptly to a lower rank. Thus the Danish astronomer Torwald Köhl had for years observed B.D. $+20°$ 1083, in the constellation Taurus, as of 7·7 magnitude, when on 22nd January 1898 he was taken aback to find it not much above the ninth.[1] Sixty per cent of its rays had been, as a consequence of some inexplicable collapse of energy, subtracted or suppressed. A step towards the bourne from which there is no returning may be taken in such cases. Stars vanish, but they seldom or never reappear. Yet renovation plays its part no less than decay. Waning stars have their correlatives in waxing stars. Alcor, the Rider, and Benetnasch, the third Horse of the Wain, are among these. Pollux, too, seems to have bettered its position, and Alcyone is far more predominant than of yore in the Atlantid family. Night's robe will still be profusely spangled, even though a few of its gems grow dim.

[1] *Astr. Nach.* No. 3475.

# CHAPTER XXIV.

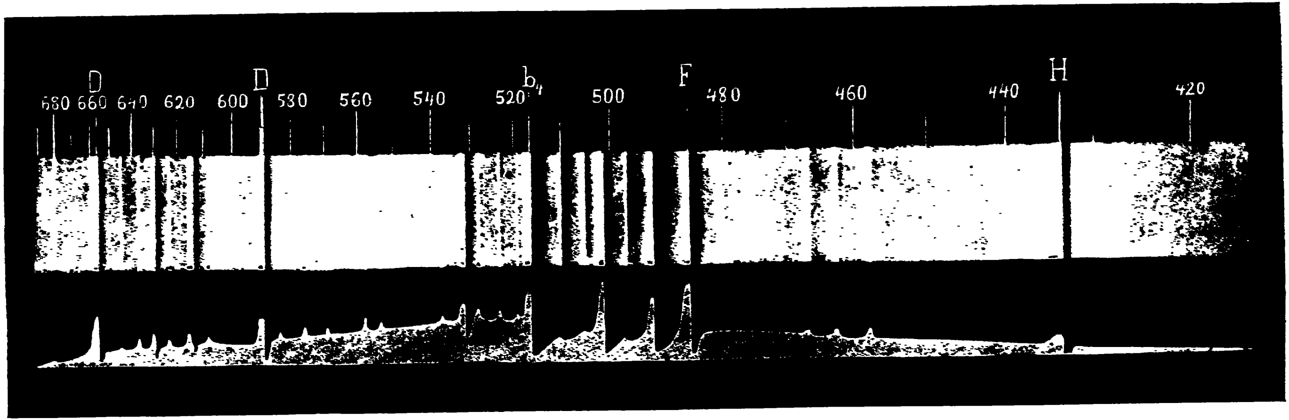
## TEMPORARY STARS.

A TEMPORARY star is a variable that rises sheer from profound obscurity to a single maximum. The maximum may be prolonged or multiple, but it must be essentially one. The occurrence of a second independent outburst would at once relegate the object to the category of irregular variables. The distinction is perhaps arbitrary, but we can only investigate by dividing. It will be best to plunge at once *in medias res* with some account of an apparition which attained to epochal importance through the efficacy of photographic methods of research.

Nova Aurigæ sprang into conspicuousness with the stealthy speed of Jack's Beanstalk. On 8th December 1891 Dr. Max Wolf took, at Heidelberg, a photograph of the sky round $\chi$ Aurigæ, showing stars to the ninth magnitude. The Nova was not among them; the spot destined for its occupation was vacant. Forty-eight hours later, as a Harvard negative attested, a fifth magnitude star filled the blank. By 20th January 1892, twelve records of this stranger's presence were included in the same series; but inadvertently, for the documents were stored up unread, and it was only through their subsequent examination that a maximum of 4·4 magnitude was inferred to have taken place on 20th December. During nearly two months, then, a new star, readily visible to the naked eye, shone unnoticed in the heavens. It was finally perceived by an amateur, Dr. Thomas D. Anderson of Edinburgh, and an anonymous post-card, by which, on 1st February 1892, he conveyed the news to Dr. Copeland, formed the starting-point of widespread astronomical activity.

The spectrum of the Nova was promptly photographed at Tulse Hill, South Kensington, Stonyhurst, Potsdam, and Mount Hamilton; eager study was devoted to its implications; and they were of a most unexpected kind. For no previous stellar apparition had been *analytically* recorded; and the similar spectral phenomena, doubtless present in Nova Coronæ and Nova Cygni, eluded definite determination with the eye. But when the turn of Nova Aurigæ came, the spectrographic method was effectively at hand, and the peculiarities of its light could be rendered obvious, salient, and permanent. Some of them were indeed visually manifest. The spectrum was at once seen to blaze with bright lines, many of them greatly widened (see Plate XVII.); and nearly all came out photographically as attended by strong dark companions on their more refrangible sides. The entire hydrogen series, from crimson C to the last of its ultra-violet associates, was thus doubled, no less than the pre-eminent calcium pair, the sodium D, and a considerable number of lines since identified as originating from helium. An exceptional feature was the predominance of "green" helium; $D_3$ and the rest of the lines belonging to the "yellow" set were comparatively faint; while λ 4922, λ 5016, and their fundamental, λ 6678, shone lustrously. Their superiority, never before observed in the spectrum of a heavenly body, results in the laboratory from heightening the exhaustion of the emitting gas; but this condition seemed to be excluded in Nova Aurigæ by the distended aspect of rays unmistakably proceeding from a more than ordinarily condensed atmospheric stratum. Unprecedented, likewise, was the simultaneous brightening of the *three* D-lines. No stellar spectrum previously observed had shown the action of sodium otherwise than by absorption. Both characteristics, it is true, may have been present in earlier Novæ, but they first arrested attention in Anderson's star.

These novelties, curious though they were, sank nevertheless into insignificance compared with one dominant trait. This was the large opposite displacements of the bright and dark sets of lines. Contrary motions of prodigious velocity appeared to be indicated, and for a time their prevalence was taken to be incontrovertibly attested. The outburst, by a consensus of




Visible Spectrum of Nova Aurigæ, 28th February 1892. Intensity-Curve below (Campbell).

opinion, resulted from the approach, and integrated the light of two components, one a bright-line star receding from the earth at the rate of about 230 miles a second, the other a dark-line star hurrying towards it with a speed of 320 miles. Soon, however, incongruities began to develop, and they grew and multiplied as time went on. To begin with, the spectral shifts underwent no alteration; the movements indicated by them—if they did truly indicate movements—persisted without abatement as the bodies animated by them withdrew from each other's vicinity to a distance greatly exceeding that of Neptune from the sun. Now velocities, to continue uniform, must be inherent; that is to say, they cannot represent the merely temporary effects of gravitational pull, since orbital acceleration is strictly balanced by retardation. Evidently, then, the components of Nova Aurigæ did not simply fall together; they should have been fabulously massive to have produced, by their mutual attraction from infinity, a speed which continued at the rate of 550 miles a second three months after the periastral rush-past, the date of which presumably coincided with the first rise to brilliancy on 10th December. Professor Seeliger of Munich[1] calculated that 15,000 times the sun's gravitative power, at the very least, must have been at work if the orbits traversed were parabolic; and the extravagance of the estimate sufficed, and was designed to compel its rejection. Hyperbolic motion was accordingly resorted to; the encountering bodies brought, it was supposed, their own velocities with them from the farthest bounds of space; and they were of so high an order that the increments due to mutual gravity left them sensibly unaltered. A pair of "runaway" stars, one moving towards, the other from the earth, must, it seemed, have accidently passed each other almost within grazing distance. They were primitively unrelated; their quasi-collision could never be repeated; they were as unlikely as any two stars in the heavens to be similar in constitution. Yet their spectra affirmed their close affinity; both were of pure helium type; one might be called the *negative copy* of the other. Nor was this all. Anomalies still more glaring presently disclosed themselves. Too obviously, on the adopted hypothesis, one

[1] *Astr. Nach.* No. 3118.

pair of meeting stars could not suffice to explain the phenomena. Vogel stipulated for a triple encounter;[1] Campbell found evidence of the interaction of four luminous masses.[2] The more attentively, in fact, the spectrum was examined, the more complex it appeared. The bright lines were not simple emanations, but groups of differently refrangible rays; the dark lines were intersected by bright threads, variable in number and position. Several distinct sets of lines, each with its separate amount of shift, and each hence associated with a differently moving mass, thus stood out independently. "On the hypothesis of four bodies," Professor Campbell wrote, "the principal system of bright lines was not displaced appreciably, and the star yielding it was practically at rest with reference to the solar system. Another system was displaced towards the red, a distance corresponding to a velocity of recession of about 315 miles a second. The system of fine bright lines, and likewise the system of dark lines, were displaced towards the violet, a distance corresponding to a velocity of approach of about 400 miles a second." The analysed light of the Nova, on this showing, consisted of four superposed spectra disconnected in their origin. The case, however, was presented with diffidence; no conclusive force was claimed for it. The spectrum, indeed, if multiple at all, was more than quadruplicate. Victor Schumann pointed out[3] that not less than six, if as many as two stars were engaged in the outburst, and planets *ad libitum* were thrown into the *mêlée* by Vogel.[4] The collision-theory, in short, collapsed under the weight of the facts it had to carry; speculation was plainly off the track; a new principle of explanation had to be sought. It was difficult to find; yet some probable though partial truths had been laid hold of. Sir William Huggins, for instance, pointed out that the complexities of the spectrum might be in part due to "reversals" in the atmosphere of a single star.[5] Such effects of the stratification of glowing vapours are common in the sun, and may be artificially produced in a diversity of forms. Their

[1] *Astr. and Astrophysics*, vol. xi. p. 393.
[2] *Ibid.* p. 810. [3] *Ibid.* vol. xii. p. 159.
[4] *Abhandlungen der Kön. Akad.* Berlin, 1893, p. 58.
[5] *Discourse at the Royal Institution*, 13th May 1892.

presence in Nova Aurigæ was clearly recognisable. The opinion, too, expressed by Father Sidgreaves might safely be adopted that the spectrum of the new star "was, on the whole, what the solar chromospheric spectrum might be expected to show on a grander scale of disturbance."[1] Finally, M. Seeliger's general theory of stellar conflagrations,[2] as arising from the passage of compact bodies through "cosmical clouds," or nebulæ, though strained to meet superfluous requirements, had fundamentally much to recommend it. Entire originality could not be claimed for it; Mr. Monck, and possibly others besides, had earlier proposed a similar view; but it was by Seeliger independently developed, and independently applied to the circumstances of the latest event. These were indeed particularly embarrassing to theorists. They seemed to imply the continuous progress of opposite radial movements of enormous velocity, and the problem of bringing them into play, whether by the rushing of inflamed gases or by the bodily transport of luminous globes, was, when considered in all its complicated bearings, formidable, if not desperate. Yet it had to be faced, for at that time spectral displacements were explicable only as effects of motion; they should perforce be interpreted on the radial velocity principle. This is no longer absolutely prescribed; the same phenomena have been found to bear other meanings—meanings not yet thoroughly intelligible, but promising, when they become so, to provide the keys to many enigmas.

We may now trace the further course of the apparition. During nearly three months it retained most of its brightness, despite wide fluctuations; then on 6th March a precipitate decline set in, bringing the object on 26th April to the limit of visibility with the great Lick refractor. In Fig. 42 the course of change so far is graphically portrayed. It was naturally believed to have reached its term; the Nova seemed definitively extinct; but in this, as in other respects, its behaviour defied anticipation. Observations resumed 17th August 1892, after its conjunction with the sun, showed, in the place of the vanished star, a stellar nebula of the tenth magnitude.[3] The recovered light was entirely altered in quality. No

[1] *Astr. and Astrophysics*, vol. xi. p. 607. [2] *Ibid.* p. 907.
[3] Campbell, *Astr. and Astrophysics*, vol. xi. p. 715.

stranger disclosure has been made by the prismatic method than that of the spectral transformation of Nova Aurigæ between March and August. The dark lines of the former spectrum had become effaced; the bright lines were no longer chromospheric but nebular. Their character, moreover, denoted disturbance of a very peculiar kind. They were wide and hazy, and some at least could be resolved into groups projected

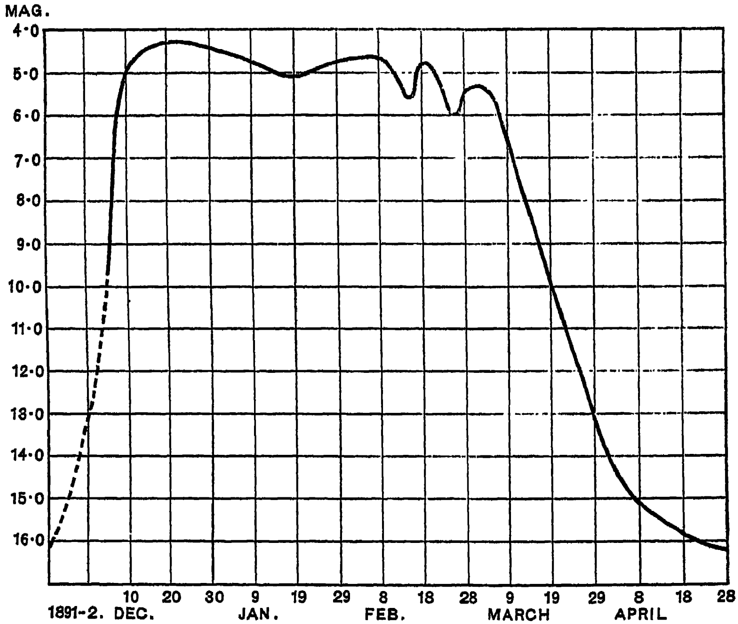



FIG. 42.—Light-Curve of Nova Aurigæ.

upon a feeble luminous background.[1] Plainly the state of things producing the complex "reversals" noted in the spring had become intensified in the reappearance of the autumn. Yet the multiple bands composing the new spectrum corresponded most faithfully, in number and mean position, with the rays of a planetary nebula. The representation was essentially perfect. Out of nineteen Nova-lines measured by Professor Campbell, only one of subordinate importance appeared foreign to nebular light.[2] Both the Wolf-Rayet blue

[1] Huggins, *Proc. Royal Society*, vol. liv. p. 30.
[2] *Astr. and Astrophysics*, vol. xii. p. 728.

bands were present, as in certain planetaries; while the distinctive, though enigmatical, nebular line at λ 373, noticed as absent from the Tulse Hill photographs of the original spectrum, emerged as it altered, and was recorded by Von Gothard at Herény in November 1892.[1] All the metallic lines, all the helium lines (except a trace of λ 4472) had died out; only those of hydrogen survived; and hydrogen glows universally. The metamorphosis could hardly have been more complete. Professor Campbell might well say that the relation of the later to the earlier spectrum was "not apparent."[2] It was certainly most obscure. At least, however, the conviction was acquired that the light "emanated from one source;" although subsequent experience obliges us to regard as fictitious the rapid approaching movement attributed to that source on what then seemed incontrovertible evidence. The presumed velocity reached a maximum of 190 miles a second in September, but in November 1892 had decreased to about half that value. And the slackening continued until, at the end of two years, the shifted lines occupied almost normal positions. Subsidence of physical agitation might safely be associated with the change. It was attended by spectral modifications of a different kind. In the transformed Nova bright lines at λ 436 and λ 575 were at first prominent. They also occur in nebulæ, but by exception and inconspicuously. Eventually they faded out, and the spectrum remained typically nebular save for the anomalous breadth of the lines.[3]

As a star, Nova Aurigæ had been decidedly yellow; in its nebular stage it assumed a greenish tint. Its chromatic peculiarities accounted for the haziness of its aspect with many refractors. Outstanding rays, left unfocussed when the rest were united, created a spurious disc of which no trace could be perceived with a reflector.[4] The revived Nova maintained tenth-magnitude lustre with trifling fluctuations for upwards of four years; then it began once more slowly to decline, and in the latter part of 1897 looked "more like a most minute and faint planetary nebula than a star."[5] In

[1] *Astr. and Astrophysics*, vol. xii. p. 54.
[2] *Publ. Pacific Society*, vol. iv. p. 246.
[3] Campbell, *Astroph. Journ.* vols. i. p. 49; v. p. 240.
[4] Huggins, *Astr. and Astrophysics*, vol. xiii. p. 239.
[5] Peek, *Journ. Brit. Astr. Assoc.* vol. ix. p. 260.

1897 it had sunk below the thirteenth magnitude; in 1900 it touched the fourteenth.[1] A partial revival was noted at the Lick and Yerkes observatories in 1901, the peculiarity of its focus continuing to indicate the nebular quality of its light.[2]

Nova Aurigæ was neither the first nor the last temporary star to don, in fading, a garb of nebular light. Nova Cygni passed through an identical phase, and the example has since been frequently imitated. Chiefly, indeed, the methods of investigation brought to bear upon it, and the novel considerations to which, in consequence, it gave rise, rendered the apparition of 1892 memorable. Its dominant features were those of a model "blaze star"; but they were for the first time decisively ascertained. An evanescent phenomenon was rendered virtually permanent, and for dubious visual impressions, definite transcripts of fact were substituted. They are likely to be multiplied in the future; and it has meantime become abundantly clear that no special theory, fitting only the circumstances of Nova Aurigæ, can be true.[3] Whatever rationale of them may be ultimately adopted, it must be one capable of general application.

The photographic era of investigation began with Nova Aurigæ, that of photographic discovery with Nova Normæ. The former object was still visible when the latter came into notice. Virtually a replica of the earlier spectrum imprinted itself upon a Draper Memorial plate exposed at Arequipa by Professor Bailey 10th July, and examined by Mrs. Fleming at Harvard College 26th October 1893.[4] It included about a dozen bright lines, each shadowed by a dark one on its more refrangible side. In position, in relative shift, in character, the system of duplicate rays matched with singular fidelity that scrutinised and wondered at in the previous year. There was then nothing casual about its production. The spectral displacements and the augmented refrangibility of the dark lines belonged to the essence of the phenomenon. Portentous velocities, specially directed, and inherent in specially constituted masses, could have had nothing to do with them.

[1] Rambaut, *Observatory*, vol. xxiv. p. 261.

[2] *Ibid.* p. 360; Barnard, *Astroph. Journ.* vol. xiv. p. 152; *Monthly Notices*, vol. lxii. p. 61.

[3] Campbell, *Astroph. Journ.* vol. i. p. 51.

[4] Pickering, *Astr. and Astrophysics*, vol. xiii. pp. 40, 398.

The appearance of Nova Normæ, then, disposed of what was left of the encountering star-theory.

The conflagration was of a strictly temporary nature. Absence from a chart-plate proved the star to have been fainter than the fourteenth magnitude, 27th May 1893; and a spectrographic plate, taken 21st June, added the information that it had not at the later date reached tenth-magnitude brightness. Its rise to the seventh, on or before 10th July, was probably effected in a few hours; but though fortunately registered at an early stage in its career, it was not recognised for nearly four months, by which time it had sunk to one-sixth of its primitive lustre. The same marvellous change witnessed in Nova Aurigæ attended its decline. On 13th February 1894 Professor Campbell[1] succeeded in observing the star with the Lick thirty-six inch, in spite of its low meridian altitude of barely $2\frac{1}{2}$ degrees. The spectrum was nebular. It consisted, to the eye, of the well-known trio of green rays, together with the golden line ($\lambda$ 575), also emitted by the transformed Nova of August 1892. Measurements of them afforded no evidence of displacement; their wave-lengths were as usual. Towards the middle of 1895 Nova Normæ became telescopically invisible. It was already provided with a successor. Just as it glimmered out, a star in the constellation Argo lit up. Nova Carinæ was detected by the same means as, though with somewhat more delay than, Nova Normæ. Two impressions of its spectrum, which chanced to be secured, on 14th April and 15th June 1895 respectively, disclosed precisely the same arrangement of coupled lines, the dark set above the bright, so remarkable in earlier examples.[2] During those two months this had not appreciably varied, but a significant change of a different kind had come about. A vivid ray at $\lambda$ 4700 (approximately), scarcely visible 14th April, was as bright as the hydrogen lines on 15th June. Its identity with the Wolf-Rayet azure band—the leader line of the Rydberg hydrogen series—may safely be assumed, and its kindling was most likely the prelude to a complete nebular transformation. But of this we have no certain knowledge, since the later history

[1] *Astr. and Astrophysics*, vol. xiii. p. 311; *Astr. Nach.* No. 3211.
[2] *Harvard Circular*, No. 1.

of Nova Carinæ remained unwritten. The conflagration was brief; it had burnt itself out before Mrs. Fleming's examination of the plates transmitted from Arequipa gave the alarm of its occurrence. Hence no express observations were feasible.

The year 1895 was prolific of temporary stars. One was retrospectively announced to have appeared in the constellation Perseus in 1887.[1] A bright-line spectrum, dimly self-imprinted upon a Draper Memorial plate exposed at that period, was at first thought to signify the rise to maximum of an ordinary Mira-variable. But the originating object soon vanished, to all seeming, definitively, and its brief incandescence asserted itself, by its non-recurrence, as that of a new star. There was a further note of distinction. The fifth line of hydrogen ($H\epsilon$), never apparent in an ordinary variable, glimmered in the peculiar spectrum of the star of 1887, which included besides an unknown line at $\lambda$ 4060.

The last record obtained of Nova Carinæ preceded the first of Nova Centauri by just a fortnight. They differed, however, widely in character. The spectrum singled out by Mrs. Fleming, 12th December 1895, from a crowded spectrographic picture taken at Arequipa 18th July in the same year, resembled that of an exceptional nebula, 30 Doradûs. It seemed abortively or imperfectly stellar.[2] The source, too, from which it emanated was situated in a nebulous environment. With the fading of its brightness—which probably never greatly exceeded the seventh magnitude—an outlying portion of a known nebula (N.G.C. 5253), momentarily effaced by the blaze, as a fire is "put out" by the sun, shimmered into view, like a halo round the dying star.[3] It still survives, while not a trace can be seen of its quondam inmate. By the time that Nova Centauri came to be recognised, it was unfortunately already far advanced on its return to obscurity. It had sunk below the eleventh magnitude on 22nd December, when Professor Campbell secured the first of three observations of its spectrum. He described it as continuous, though peculiar, for the blue section was of disproportionate strength, and the yellow showed inequalities, as if through the

[1] *Harvard Circular*, No. 4.

[2] *Ibid.* No. 4; *Astroph. Journ.* vol. iii. p. 214.

[3] W. J. Hussey, *Astr. Journ.* No. 383; *Publ. Pacific Society*, vol. viii. p. 220.

superposition of bright lines.[1] A parting glimpse of the strange star was caught by Professor Hussey at Lick on 16th July 1896. It was then excessively faint, and immersed in nebulosity. The analogy between this apparition and that which illuminated the great Andromeda nebula in 1885 was unmistakable, and both diverged significantly from the type of Nova Aurigæ.

It was reverted to by Nova Sagittarii. This star was photographed at Arequipa 8th March 1898, and identified by Mrs. Fleming as "new" a year later.[2] Yet it was at maximum fully the equal of Nova Aurigæ, and might have been seen at a glance by any one familiar with sky scenery. It waned, however, very speedily. It was of only 8·2 magnitude on 19th April, when a spectrographic record chanced to be secured, and had declined to the eleventh before its deliberate investigation became possible. Plate XVI. Fig 4, reproduces two spectral photographs of Nova Sagittarii, obtained within forty-eight hours of each other. Six or seven hydrogen lines are shown in them, broad and bright, but without the dark companions usually visible in such spectra. The second band from the right is the more refrangible of the Wolf-Rayet blue radiations ($\lambda$ 4643); the K of calcium is absent, but six sharp rays, identified with chemically unclaimed lines in the spectrum of Nova Aurigæ, came out distinctly on the negatives. Although taken at so brief an interval, the records disagreed in some particulars. Thus the unknown line at $\lambda$ 4060, emitted by the first Nova Persei (1887), was strongly absorbed in Nova Sagittarii on 19th April, but had vanished on 21st April; while the chief nebular line, invisible at the earlier, shone at the later date. The initiated change did not stop here. In March and April 1899 a purely nebular spectrum was derived from the semi-extinct object by Professors Campbell and Wright.[3] The regular cycle had been run through; a planetary nebula replaced the faded star. In one important respect, nevertheless, Nova Sagittarii had departed, so far as the extant data could inform us, from the pattern set by Nova Aurigæ. The spectrum, as already mentioned, was

[1] *Astroph. Journ.* vol. v. p. 233.

[2] *Harvard Circular*, No. 42; *Astroph. Journ.* vol. ix. p. 269 (Pickering).

[3] *Ibid.* p. 308.

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single, not duplicated by absorption. But there is good reason to believe that this difference did not originally exist; it supervened with the declension of light. In "temporary" spectra the bright lines always seem to survive the dark; the chiaroscuro effect is produced only near the period of maximum, and this period had terminated before the star of 1898 was spectrographically registered. Earlier impressions, we may be sure, would have displayed the coupled lines symptomatic of the enormous disturbances attending these extraordinary outbursts.

Their frequency, established by the camera, is a fact of subversive import, but has already ceased to excite surprise. The recognition of the autographs of new stars has become a regular part of the business conducted at such a "Solomon's House" as the Harvard College Observatory. In the *Annual Reports* thence issued the mention of new stars has grown to be habitual and familiar. Of Nova Sagittarii the last had only just been heard, when Nova Aquilæ was announced to have appeared.[1] This was about fifteen months after date. The star made its *début* on a Draper Memorial chart-plate 21st April 1899 as an object of the seventh magnitude, and displayed the quality of its light in a spectrograph taken 3rd July. It was characteristically that of a Nova, although nebular lines had begun to come in, and the transformation was completed in the course of September. During a year, Nova Aquilæ wore the aspect of a planetary nebula, sinking gradually from the tenth to the twelfth magnitude. It was last observed by Professors Campbell and Wright with the Lick thirty-six-inch refractor and a 60° prism spectroscope. "The visible spectrum," the former wrote,[2] "consisted of extremely faint continuous light in the green, and of three bright bands in the positions of the three principal nebular lines. The relative intensities of the three bands agreed approximately with the corresponding intensities in the well-known nebular spectra. The bands were not monochromatic, but on the contrary were very broad, perhaps fully twice as broad as the bands in the nebular spectrum of Nova Aurigæ in August 1892."

It may be useful to tabulate the results, in the discovery

[1] E. C. Pickering, *Astroph. Journ.* vol. xii. p. 52; *Harvard Circular*, No. 56; *Astr. Nach.* Nos. 3651, 3664.

[2] *Astroph. Journ.* vol. xii. p. 258.

of new stars, of the photographic surveys executed at Harvard College and at Arequipa, its southern dependency.

(i.) Nova Persei. Appeared 1887; ninth magnitude; hydrogen lines and λ 4060 bright. Temporary character recognised 1895.

(ii.) Nova Normæ. Spectrum photographed 10th July 1893; character detected 26th October 1893. Seventh magnitude; showed twelve bright lines coupled with more refrangible dark ones; spectrum nebular 13th February 1894.

(iii.) Nova Carinæ. Spectrum photographed 21st April 1895; examination followed in October. Hydrogen lines bright with more refrangible dark companions. Faded from eighth to eleventh magnitude between April and July.

(iv.) Nova Centauri. Spectrum photographed 18th July 1895; irregularly continuous; resembled that of 30 Doradûs. Character detected 12th December 1895. Maximum magnitude 7·2. Situated within a nebula.

(v.) Nova Sagittarii. Photographed 8th March 1898, when of 4·7 magnitude; detected March 1899. Spectrum photographed 19th and 21st April 1898. Hydrogen lines bright; no dark companions; λ 4060 dark. Spectrum nebular, 13th March 1899.

(vi.) Nova Aquilae. Photographed 21st April 1899, when of seventh magnitude. Bright-line spectrum photographed 3rd July 1899; recognition ensued in July 1900. Spectrum nebular, October 1898.

In the course of seven years, then, five temporary stars were photographically discovered, and it is safe to assert that all would have escaped direct visual notice. Apparitions of the kind are, we hence learn, hardly to be counted as exceptional; their occurrence cannot depend upon rare contingencies, but must enter, to some extent, into the regular economy of nature. The conditions precedent are doubtless widely prevalent, and they are the same for outbursts of all magnitudes indifferently. The famous Novæ of history—the stars of Hipparchus, of Tycho Brahe, of Kepler—were due to just such prepared accidents as result, more frequently and less obtrusively, in the appearance of an extra dark dot on a chart-plate, or in the emergence, on a prismatic negative, of a "peculiar" spectrum among a crowd of normal ones.

But this obscure kind of manifestation was far transcended by the "New Star of the New Century" (to quote Father Sidgreaves's designation of Nova Persei, No. 2). This object worthily commemorated the turning of a leaf in the book of ages. The sidereal heavens had harboured no such brilliant "guest" since Kepler's star shone in Ophiuchus. Dr. Anderson, the discoverer of Nova Aurigæ, was still more lucky with Nova Persei, for he caught it on the rise. It was, however, already nearly the equal of Algol when he sighted it in the early morning of 22nd February 1901; while twenty-eight hours previously, as a photograph taken by Mr. Stanley Williams attested, it must have been fainter than the twelfth magnitude. Confirmatory evidence was derived from the Harvard College series, two specimens of which are reproduced in Fig. 43 by the kind permission of Professor Pickering. In the earlier photograph, taken with an exposure of sixty-six minutes 19th February, no trace of anything unusual is perceptible; in the second, to which, seven days later, a shorter exposure was given, the Nova is of dominating importance. It continued to gain light rapidly for about a day and a half after its detection at Edinburgh. On the evening of 23rd February, it was observed through drifting clouds at Harvard College to be brighter and bluer than Capella.[1] In thirty hours it had increased by two and a half magnitudes; during that one night it took rank as the premier star of the northern hemisphere. But its supremacy was quite transient. Increase was at once followed by decrease; there can have been no appreciable pause at maximum. Already on 24th February, the star had lost fully one-third of its light; the inevitable downward course was entered upon, and was pursued, although with singular intermittences. But the most remarkable characteristic of Nova Persei was its spectral variability. It showed, to begin with, a spectrum of the ordinary Orion type—a continuous prismatic strip, scarcely encroached upon by narrow lines of hydrogen and helium absorption. Some of these, it is true, proved on close examination to have their lower edges slightly brightened, but there was no other sign of disturbance. On the following night it was noticed that the K of calcium,

[1] *Harvard Circular*, Nos. 56, 57.

1.

2.

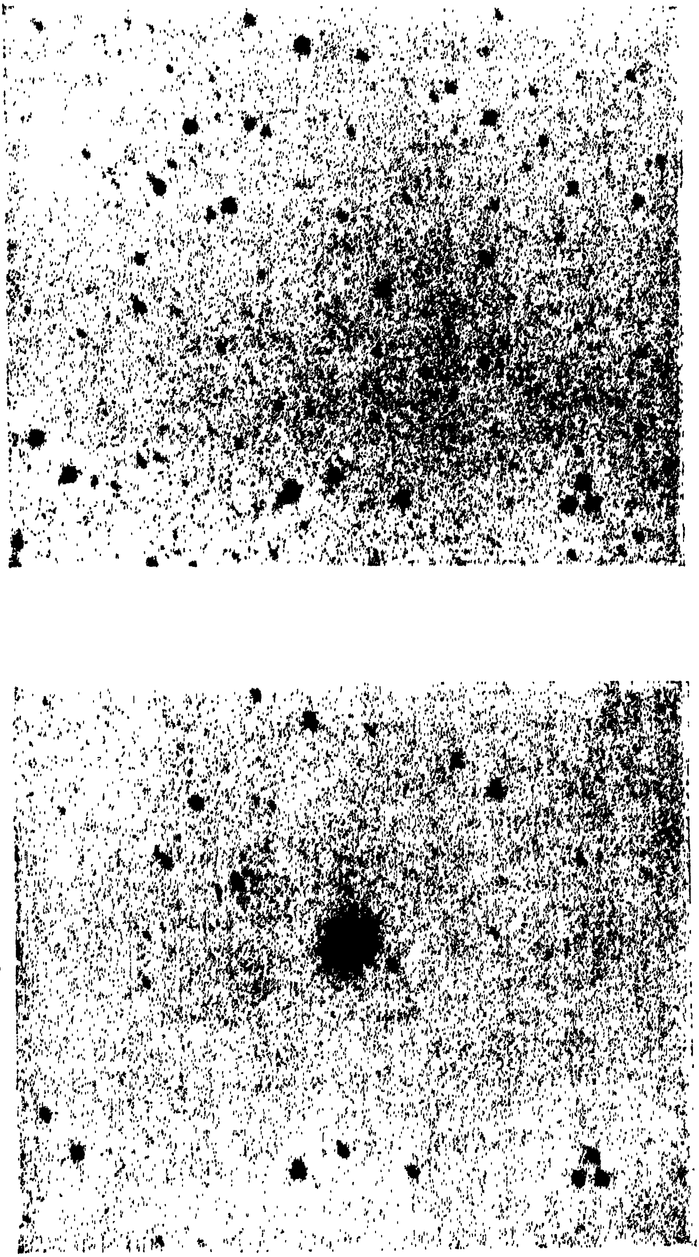


Fig. 43.—Photographs of the same field taken at Harvard College before and after the outburst of Nova Persei. No. 1, 19th February 1901. No. 2, 26th February 1901.

previously imperceptible, stood out markedly obscure, after which an extraordinary change took place. During the twenty-four hours that followed the maximum of 23rd February, the character of the spectrum was completely transformed. Hydrogen now blazed in it; and the range of broad bright lines representing its emissions was duplicated, just as in Nova Aurigæ, by a range of more refrangible shadow-bands. These were strongly displaced towards the violet, and their displacement appears to have increased progressively for some days. It finally corresponded, if interpreted on the Doppler principle, to an approaching velocity of about 1000 miles a second, while the bright lines, so far as their distended condition allowed a judgment on the point to be formed, retained pretty nearly their usual places. The Doppler principle, however, had plainly a very restricted application to the case of Nova Persei. Dr. Vogel[1] used it, with excellent judgment, to determine the star's true radial motion from measurements of fine dark reversals of H and K, which seemed entirely exempt from alterations of a physical kind. He found it to be about twelve miles a second in a direction away from the sun. He was less successful in his endeavour to explain the conspicuous shifting of the dark hydrogen lines on the pressure-theory as adapted by Wilsing. For pressure does indeed alter the refrangibility of the rays emitted by vaporous strata submitted to it, but the alteration is always in the same sense. The refrangibility of light is diminished by condensation; the resulting spectral displacements are towards the red. Nevertheless, those of the absorption lines in Nova Persei were towards the blue. Nor was the masking arrangement devised for the purpose of smoothing away this fundamental contradiction, one that would work. The star itself, through the gradual unfolding of its peculiarities, emphatically disavowed it. A Stonyhurst spectrograph of 7th March showed the dark hydrogen lines well separated from the bright;[2] they were unmasked, yet none the less shifted. Their altered positions were thus seen to be those of the rays in their entirety, and not merely of outlying wings left visible, while their central parts were

[1] *Sitzungsberichte*, Berlin, 21 März 1901.

[2] Rev. W. Sidgreaves, *Observatory*, vol. xxiv. p. 192.

concealed. Subsequently to 7th March these lines thinned off, and in about a fortnight disappeared finally. The spectrum

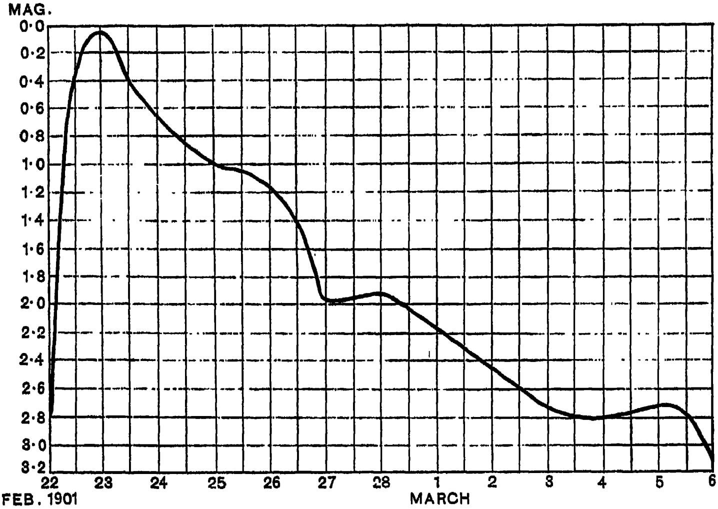



FIG. 44.—Light-Curve of Nova Persei, 22nd February to 6th March 1901.

then remained in much the same condition as that of Nova Sagittarii at the date of the earliest record of it; the

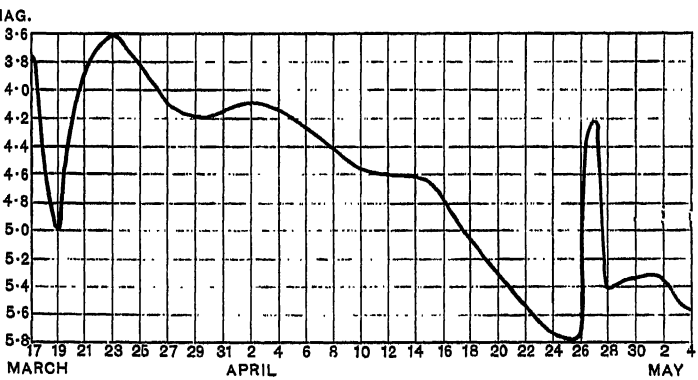



FIG. 45.—Light-Curve of Nova Persei, 17th March to 4th May 1901.

distinctive chiaroscuro effect was gone; the bright lines no longer *cast shadows.*

Sections of the light-curve of Nova Persei are delineated in Figs. 44 and 45. They seem to tell of a long succession

of efforts towards recovery, constantly defeated by the invincible advance of exhaustion. These variations in magnitude were associated with remarkable spectral modifications. The light of this wonderful object was, from the first, of extremely unstable quality. The emitting and absorbing vaporous layers were evidently in a state of continual flux. Their turmoil was betrayed by changes of intensity, width, and wavelength in both dark and bright lines, most of them taking place unconnectedly, so to speak, and capriciously. By degrees, however, their confusion reduced itself to some kind of partial order. During the month of March, Nova Persei assumed the character of a variable fluctuating extensively in a period of three days, and the spectrum was found to vary quite decidedly in correspondence with the light. The phenomena of its alternations are illustrated in the subjoined reproductions of photographs taken by Father Sidgreaves (see Plate XVI. Fig. 5). The second and fourth are distinctive of minimum epochs; the first and third characterise much higher grades of brightness. Among the features of the minimum spectrum are the fading of the continuous radiance, the displacement upward of the first ultra-violet member of the hydrogen series (H$\zeta$), and the development of a blue band at $\lambda$ 463. The two types of spectrum continued to succeed each other with approximate regularity from 19th March to 3rd May. Numerous anomalies, indeed, presented themselves. They were described in detail by Fathers Sidgreaves [1] and Cortie,[2] by Lockyer, Pickering [3] and Hale,[4] but no clue to their physical interpretation has been found. Only those affecting one narrow region of the spectrum can here be further adverted to. The appearance of the D-lines in Nova Persei was most remarkable. Special attention was paid to them at the Yerkes Observatory, and they are delineated in Plate XVI. Fig. 3, from a photograph taken on an "Erythro" plate with the forty-inch refractor of that establishment. The relations of the various lines shown in it need some brief explanation. The broad bright band is due to the radiation of sodium; the fine dark lines projected upon it are obvious reversals by a cooler and rarer overlying stratum

[1] *Monthly Notices*, vols. lxi. pp. 388, 462; lxii. p. 521.
[2] *Ibid.* vol. lxi. p. 464.
[3] *Harvard Circular*, No. 59.
[4] *Yerkes Observatory Bulletin*, Nos. 16, 17.

of the same metallic vapour. These threads of absorption are slightly displaced towards the red; they indicate about the same rate of recession from the earth that was derived by Vogel from the similar reversals of H and K. The fact, then, admits of no doubt that the kindled mass was travelling away from us with a small velocity.[1] This remained constant—so far as our information goes—from first to last; but the position of bright D underwent a marked alteration. The broad bright band, traversed almost centrally in the early days of March by hair-like reversals, shifted in the course of a month so notably towards the blue that the fiducial lines (as they might be called) lay in April close to its less refrangible edge; while the absorption line concealing $D_3$ had meantime become diffused towards the violet. We have no inkling of a possible cause for these changes. They were steadily progressive, and so disclaimed any immediate connection with the periodical variations of the $H\zeta$ line. According to Father Sidgreaves's view, indeed, these last originated from no change of refrangibility, but from the brightening of a cyanogen band situated just above the hydrogen line it illusorily modified. The sodium band, however, actually moved upward; the emitting molecules quickened their vibrations through some unknown kind of influence. Only the less refrangible members of the helium-series glowed in this marvellous spectrum. None higher up than the blue "Orion" line at $\lambda$ 4472 could be seen; while the blood-red $\lambda$ 6678, and $D_3$ (when sodium-absorption thinned off) shone intensely.

The colour of Nova Persei changed from white to red a few days after its maximum on 23rd February, and red it remained for some months. The tinge, indeed, lightened to clear orange in its spasms of recovery, but deepened to a purplish glow at each subsequent decline. It faded completely in July 1901, when the spectrum of the Nova resembled that of a planetary nebula.[2] Plate XVIII. Fig. 2 illustrates, from the Lick observations, the predominance in it, on 11th August, of the leading nebulium-radiation. This was in

[1] This was assured by Campbell's determinations (*Lick Bulletin*, No. 8).

[2] *Lick Bulletin*, No. 8; Sidgreaves, *Astr. Nach.* No. 3741; Von Gothard, *ibid.* No. 3738.

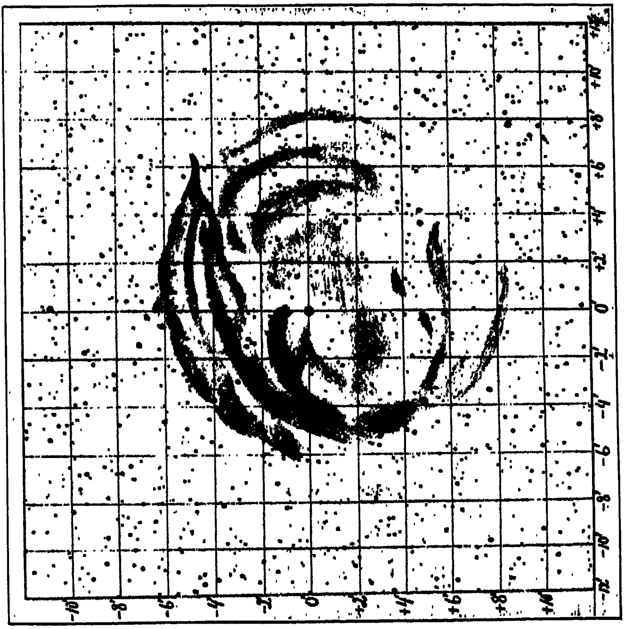
accordance with precedent; but the wildest flights of imagination were outrun by what ensued.

On 22nd and 23rd August 1901, Professor Max Wolf took long-exposure photographs of the Nova with the sixteen-inch Bruce objectives lately mounted as a twin-telescope at Königstuhl. Both plates showed the presence of detached nebulous masses to the south-east of the star;[1] and these proved to be only the brightest parts of a vast spiral formation photographed by Mr. Ritchey at the Yerkes Observatory on 20th September, under the form represented in Plate XVIII. Fig. 1.[2] Its intimate structural relationship to the star is patent; but there was more to come. Renewed impressions obtained 7th and 13th November with the same instrument—a twenty-four-inch reflector of his own construction—showed Mr. Ritchey that the nebula was expanding with portentous speed;[3] and an identical discovery was made by Mr. Perrine from a comparison of the Yerkes photograph of 20th September with a Crossley picture secured by a duplicated exposure 7th and 8th November.[4] The movements indicated were at the rate of about one minute of arc in five weeks; and they were maintained until the dimly shining spires affected by them faded into chemical invisibility. Moreover, the spinning of the nebulous web was found to have been an initial accompaniment of the stellar outburst. Two close coils of it were discerned by Mr. Perrine on scrutiny of a negative exposed for ten minutes 29th March 1901.[5] And since they were closer in the ratio of their expansion between September and November, it became evident that the process had gone on unchecked during seven or eight months; while the tracing of it backward showed it to have actually commenced almost simultaneously with the kindling of the conflagration. That is to say, the rate of flow of the nebulous streams indicated their issue from the Nova about 17th February, or five days previously to its visible manifestation.

Speculation regarding this unique phenomenon has naturally been active; and an explanatory hypothesis of considerable

[1] *Astr. Nach.* Nos. 3752, 3753.
[2] *Astroph. Journ.* vol. xiv. p. 167.
[3] *Ibid.* p. 293.
[4] *Lick Bulletin*, No. 10.
[5] *Ibid.* No. 14.

1.



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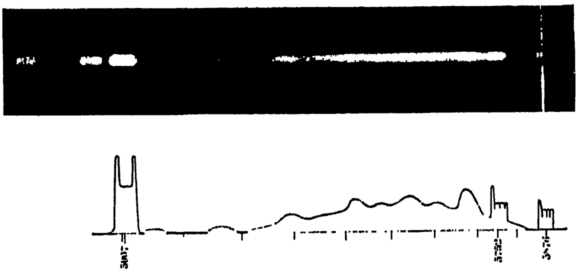


1. Nebulosity round Nova Persei (Ritchey).
2. Spectrum of Nova Persei, 11th August 1901, with corresponding Intensity-Curve (Campbell and Wright).

plausibility was hit off independently by Professor Kapteyn [1] and Mr. W. E. Wilson.[2] It affirms the nebula to have been pre-existent, and to remain unchanged. But since we see it by the reflected light of the Nova, its various spires and condensations have come successively into view as the flare of the explosion travelled outward in widening circles. Hence an illusory effect of radial expansion was produced, while, in point of fact, the temporarily illuminated cosmic folds were as immovable as aligned snow-peaks, in turn set aglow by the rising sun. The parallax corresponding to this rationale is $0''\cdot011$; it implies that the Nova actually blazed in the third year of James I. (1605), and rose to a culminating splendour eight thousand times that of our sun. In this, at least, there is no improbability. The star is devoid of sensible parallax or proper motion; and its distance from the earth cannot, accordingly, be expressed in "numbers that have name."

A strictly temporary character may safely be ascribed to its nebulous appurtenances; they were either evolved from its mass, or rendered luminous through its influence. Professor Max Wolf suggested the propagation of electric waves of the Hertzian type as the cause of the far-spreading excitement attested by the gleaming annuli. Professor Very [3] inclined to regard them as constituted by material corpuscles, such as give rise to cathode-rays, ejected from the star under the stress of light-pressure or electrical repulsion. There was, however, as Mr. Louis Bell [4] remarked, no evidence of acceleration, consequently none of the continued action of a repulsive force; while the supposition that the nebula round Nova Persei had been photographed by reflected light was, in his opinion, discredited by the absence of polarisation-effects, as well as by the long persistence of strongly nebulous patches close to the star, which, unless they had been self-luminous, should have vanished with its fading. Their light, accordingly, is surmised by Mr. Bell to have been of an auroral nature. It developed as a secondary consequence of electro-magnetic strains, propagated through space with the velocity of light, from a sun-like centre of disturbance.

[1] *Astr. Nach.* No. 3756.
[2] *Nature*, 30th Jan. 1902.
[3] *Astr. Nach.* No. 3771.
[4] *Astroph. Journ.* vol. xvi. p. 38.

What cannot be gainsaid is that the apparition, with its strange attendant circumstances, ranks as the most interesting on record. Even the classic Nova Aurigæ was far outdone by the surprising diversity of the phases, both spectral and luminous, exhibited by its brilliant successor. Their study afforded much new knowledge, and opened wide tracts for future experiment and research. A critical point of difference between the observations made on the two occasions was the timeliness of those on the latter star. They were in full swing while it was still mounting towards the summit of its splendour. As a consequence, the order of its spectral phenomena was clearly ascertained and proved wholly unexpected. At the outset, the light was of ordinary quality; waning had already set in before the displacements and distension of its linear ingredients announced the prevalence of disturbance. This fact is full of meaning; let us weigh it well. We learn from it that the sudden development of luminous energy was essentially of photospheric origin. Gaseous eruptions and explosions followed, and produced the duplicated spectrum characteristic of temporary stars. But they were merely incidental to the primary event, which occurred independently of them. This disclosure narrows the field of speculation as to the nature of that primary event, and is so far enlightening. Further, we now know that the symptoms associated with prodigious radial velocities were not inherent, but consequential. The obscure body abruptly kindled to vivid incandescence gave no evidence of rapid motion; it seemed a leisurely traveller through space.

We may now attempt to arrange and generalise the items of information lately gained about Novæ. Three have appeared in nebulæ or clusters—Nova Scorpii in 1860, Nova Andromedæ in 1885, and Nova Centauri in 1895. Set apart by their nature no less than by their situation, they were evidently transient adjuncts to the formations in which they were immersed, and *probably* imitated their luminous peculiarities. Our knowledge of them, however, is partial and unsatisfactory. Passing on to "blaze stars" proper, we note the following circumstances as common to the class.

1. They have their habitat in the Milky Way. Nova Coronæ alone had any considerable galactic latitude.

2. None have any sensible parallax or proper motion. They must then be vastly remote.

3. They rise from and relapse into approximate obscurity. The one *known* star distinguished by a temporary flare was Nova Coronæ. Several, nevertheless, continue perceptible in their effete state.

4. The bright lines of Novæ are coupled with dark lines of shorter wave-lengths. This mode of juxtaposition is invariable.

5. The spectra of Novæ resemble, in their early stages, that of the solar chromosphere, later that of nebulæ, the emissions of hydrogen and helium ultimately yielding their predominance to the green rays of nebulium. The Wolf-Rayet blue bands generally make an intermediate appearance.

Now what may we legitimately conclude from these varied phenomena? Very little, unfortunately, of a positive nature; we must be content, in the main, with negative inferences. Yet it is no small advantage to clear the ways of thought by abolishing untenable hypotheses. It may then safely be stated that the remarkable spectral shiftings in temporary stars are not effects of translatory motion; they supply no argument for the duplicity of the light-source. Neither do they originate through pressure, which tends to damp down vibrations, not to accelerate them; and it is chiefly a shortening of wave-lengths that has to be explained. Staggered by this difficulty, Dr. Wilsing suggested[1] the alternative view that Novæ are not incandescent, but "luminescent" bodies. The distinction, first made by E. Wiedemann,[2] is valid and valuable, although next to nothing is known about the essential conditions upon which it rests. All that can be said is that they involve the production of light to a great extent without heat. But the supposition that they are found in temporary stars is an extremely hazardous one. It is countenanced only by the one fact that emissions due to luminescence are, or may be, accompanied by corresponding absorptions of greater refrangibility, and so present a colourable imitation of the perplexing chiaroscuro spectrum displayed during stellar outbursts.

On the whole, the most promising theory of their occurrence

[1] *Astr. Nach.* No. 3603.

[2] *Vierteljahrsschrift Astr. Ges.* Jahrg. xxxi. p. 258.

is that stars in the Milky Way occasionally get entangled in the diffused nebulosities with which that region abounds, and blaze through the resistance offered to their motion, just as meteors kindle to brief splendour in shooting athwart our cloud of "circumfluous air." We must, it is true, be content for the present to accept it in principle; attempts to elaborate it in detail can only, until much fresh knowledge has been acquired, result in failure. Even M. Seeliger's[1] ingenuity did not avail to conduct him to a successful issue. He demanded too much from the star-and-nebula hypothesis—demanded, indeed, more than the conditions (as we now know) actually required; and it hence incurred unmerited discredit. Admitted provisionally, it will perhaps serve as a guide to ultimate truth. An important discussion of the possibilities connected with it, and of the manner in which they might serve the purposes of spectroscopic interpretation, was published by Mr. J. Halm of the Edinburgh Observatory in July 1901.[2] Proceeding from the hypothesis that a Nova becomes visible when "a dark body impinges upon, and penetrates into a mass of nebular material," he constructed a vorticose system of radiating and absorbing gases travelling with the great intruded globe, and skilfully adapted in all its parts to give rise to the observed phenomena. His arguments are not, scarcely indeed could be, in all respects convincing; yet they form a contribution of stimulating quality to the general doctrine of temporary stars. This has wide bearings. It should include, not only a rationale of the actual conflagrations, but also some definite and consistent view as to the previous state and history of the bodies subjected to them. They are glibly designated "dark stars," but embarrassments supervene when we attempt to give precision to our conceptions of what constitutes a "dark star." We will, nevertheless, essay the task in the next chapter.

[1] *Astr. Nach.* Nos. 3118, 3187, 3598.
[2] *Nature*, vol. lxiv. p. 253.

# CHAPTER XXV.

## DARK STARS.

DARK stars are of sun-like dimensions, but of planetary obscurity. They constitute a realm scarcely penetrable by direct investigation, and therefore eminently inviting to speculative thought. They are indefinitely numerous; they may be, in many cases, enormously massive and bulky; they are probably endowed, in general, with very high velocities; some are perhaps among our nearest neighbours in space. They exist both in a solitary and in an associated condition. The dynamical relations of unattached dark stars, although of the deepest interest, from their bearing upon large questions of sidereal construction, are unknown, and seem likely long to remain so; but in mixed systems of shining and obscure bodies they are readily open to investigation. Such systems occur quite freely, as we learn from observations of three distinct kinds. Their unseen members variously betray their presence: (i.) by perturbing the orbital movements of visually double stars; (ii.) by occasioning periodic changes of velocity in visually single stars; (iii.) by occulting their bright primaries, and so causing them to be affected with a special type of variability. In the first case, the effects can be discerned telescopically, in the second they come out spectrographically, in the third they are both photometric and spectrographic. Solitary dark globes, on the other hand, are brought within our ken in only one fashion. Given a certain combination of circumstances of a barely conjecturable nature, they leap into light as Novæ, and in this capacity attain various degrees of notoriety.

The existence of an "invisible" department in astronomy

was divined by Laplace; it was demonstrated by Bessel through his discovery, with the mind's eye, of the semi-obscure satellites of Sirius and Procyon. Its importance cannot well be exaggerated. Unseen bodies may, for aught we can tell, predominate in mass over the sum-total of those that shine; they supply possibly the chief part of the motive power of the universe. They appear, at any rate, to be profusely distributed throughout its compass. One star in six, by a fair estimate, is a spectroscopic binary; and spectroscopic binaries commonly disclose their nature, not by the doubling, but by the shifting of their spectral lines. This is as much as to say that one of the revolving masses radiates imperfectly or not at all. Again, temporary stars presumably rise from crowded ranks. For every one that blazes into view, multitudes must remain undistinguished. The raw material of such outbursts is doubtless lavishly provided, while the accidents actually occasioning them must be few. Stellar apparitions thus derive extraordinary importance from their implication of an unfathomable background stored with effete or undeveloped suns, the presence of which evades immediate cognisance.

"Dark stars" need not be absolutely obscure. Some, at any rate, may be feebly luminous, though powerfully attractive, like the companions of the Dog stars. These, if situated much nearer to their primaries, would escape telescopic recognition, and could challenge spectrographic notice only indirectly, through the motion-displacements due to their influence on the brilliant spectra superposed upon, and effacing their own. In other cases, stars are swayed from their computed paths by the power of entirely rayless satellites. The fourth member of the system of ζ Cancri, and the hypothetical third component of 70 Ophiuchi appear to be dark in the strictest sense. Most probably an indefinite number of gradations connect the planetary and sun-like states. Thus in some Algol pairs the occulting body is to our appreciation obscure; in others it gives some, though very little light; while in a third variety the companions stand on the same level of lustre. Algol itself, U Cephei, and Y Cygni specifically exemplify these differences. They manifest themselves as well in non-eclipsing spectroscopic binaries. A minority,

headed by $\beta$ Aurigæ, consist of globes fully luminous; a few, such as $a$ Virginis and $o$ Leonis, show traces of a second spectrum; but most are real crypto-doubles, only one member of which emits any perceptible light. With these the heavens may be said to swarm.

A number of interesting questions are suggested by the vast numbers and singular relationships of dark stars. What is their history? What their destiny? What their function in the universal scheme of things? The view commonly taken of them is that they are antiquated suns—suns in a state of senile decay—suns that, having used up their radiative vitality, are relegated to a lower cosmic plane. Such there must be, unless regenerative machinery be at work to supply, in some unimagined way, the perennial waste patent to our senses. Suns wear out, yet do not incur annihilation. They must survive their faculty of shining. Immense, but strictly limited reservoirs of energy, they are constructed, not for its economical storage, but for its rapid expenditure. Its exhaustion, which, to our apprehension, is simply a question of time, will leave them gigantic earths, solid, inert globes, with only their gravitative force unimpaired. That quondam-suns of this description pursue their unnoticed journeys through space, cannot reasonably be denied; they undoubtedly swell the hosts of dark stars; yet there are indications that these are not mainly of the effete quality—that they do not merely represent the *caput mortuum* resulting from one inexorable evolutionary process.

The frequent association of obscure with brilliantly luminous stars is very remarkable. Algol and its companion make a typical instance. They are assuredly of contemporaneous, and, judging by the usual criteria, of comparatively recent origin. The closeness of the system formed by them denotes, on the theory of tidal evolution, that it has, during no very long time, been subject to such modifying influence; and Algol itself bears all the marks of stellar juvenility. Another specially instructive example among non-eclipsing binaries is afforded by Castor. Here a great Sirian sun has an obscure and a brilliant attendant circulating respectively in less than three days and in several hundred years. Now the remote component must have separated from the parent sphere

long before the close satellite came into being; yet it is at the acme of vitality, while that of the junior star is, so far as radiative symptoms can tell, already spent. Nor is there any warrant for assuming that they differ considerably in mass. Indeed, whatever disparity there may be is just as likely as not to be *in the wrong direction.* A doubt thus arises whether the shining of suns depends solely upon temperature; for gradations of cooling cannot possibly account for the abrupt contrasts of luminosity met with in mutually revolving globes. Irresistibly the hypothesis presents itself that, among the varieties of the cosmos, there may be a multitude of bodies conditioned in most respects like suns, but which have never attained to the possession of a photosphere, and have consequently remained imperfect radiators. The formation of the dazzling cloud-shell by which suns are visibly bounded, is a baffling enigma. It must involve an intricate combination of circumstances, not always perhaps realised. Should any of them fail, a "dark star" would result—a body intensely hot, yet destitute of the apparatus requisite for the effective diffusion of light and heat.

We can now see that the obscurity of temporary stars previous to their sudden illumination does not necessarily imply that they were effete. Their galactic preference also argues the contrary. The Milky Way is apparently a region where development has not gone far. Things are there more nearly in their primitive state than elsewhere in the sidereal world. Growing and flourishing suns seem to congregate in that vast gathering-ground, rather than those that have seen better days. Hence, if stellar apparitions signified the re-kindling of stars sunk to extinction through age, the Milky Way is precisely the part of the heavens in which we should least look for their occurrence. That they frequent it almost exclusively, helps to convince us that their antecedent dimness was not due to decrepitude. This inference is confirmed by the character of their spectra. The light suddenly acquired has the quality considered to mark an early stage of sidereal development. The blaze of a helium star can with difficulty be supposed to proceed from a highly-condensed or semi-solidified body.

Dark stars must then, on this showing, be divided into

two classes, the first consisting of suns on the retired list, the second, of those incapacitated by nature for active service. Their discrimination in practice can scarcely be effected, with our present resources, otherwise than tentatively or by conjecture. Still it may not be in all cases hopeless. To take one instance. The system of 61 Cygni is held by Wilsing of Potsdam to include one or more unseen members. If so, their place—since the associated group bears many marks of antiquity—should be found among lapsed suns. And this suggests the further thought that, in a few more ages, the entire family may have ceased from radiation, and will continue, in the rayless void, to fulfil their mutual rounds and pursue their way towards an unknown goal. That many such blind systems exist, inaccessibly to observation, is a conjecture which can neither be verified nor refuted.

# CHAPTER XXVI.

## THE GENERAL QUESTION OF STELLAR VARIABILITY

THE variability of stars is a "wood of error." There seems no exit from it; the tracks that invite our ideas to enter upon them turn out circuitous and misleading. Yet its exploration need not therefore be abandoned as hopeless; and indeed lines of approach are converging upon it from many directions in a manner that promises well for the future elucidation of much that is still mysterious. In the meantime, we can at least attempt to arrange the known facts in some kind of definite order.

Stellar light-change is of two fundamentally separate descriptions. The first may be termed "extrinsic," because it obviously depends upon circumstances not inherent in the bodies it affects; the second, "intrinsic," as resulting from constitutional peculiarities. They are readily distinguishable by the nature of their time-relations. Punctuality marks the former kind, a large measure of irregularity the latter. The difference becomes intelligible if we admit, as we reasonably may, that short-period or extrinsic variability belongs exclusively to compound objects, long-period variability to solitary masses. In no case—except where darkening by eclipse unmistakably occurs—can we define the kind of action to which the observed vicissitudes are due; but the power lately acquired of discerning between the "forced" periods prescribed by orbital relations and the "free" periods determined by fluctuating interior conditions, marks an important step in advance. The circumstance, although unaccountable, should not be lost sight of that eclipsing and non-eclipsing variables diverge somewhat emphatically in the character of their spectra. Those

of Algol-stars belong to the first type, often to the helium division of it; those of Cepheid stars are mostly solar; and although enlarged experience may tend to invalidate these generalisations, it may, on the other hand, serve to reaffirm them. The spectrographic study of globular clusters—a task for the immediate future—should help greatly to widen the bases of knowledge regarding this curious relation; and the diligent collection of illustrative instances, by limiting the extent of its prevalence, may throw some light upon its cause.

The secret of short-period variability offers few points open to attack; but an attempt might be made to penetrate some of its outworks by comparing the systemic conditions of steadily lustrous close binaries with those of pairs fluctuating in magnitude. Stars of the same spectral class should, for the avoidance of complications, be chosen for confrontation. Polaris, for instance, $\theta$ Ursæ Majoris, $\lambda$ Andromedæ, are solar orbs revolving swiftly round invisible companions. In what respects, it will be of interest to ascertain, do their orbits differ from those of the variables $\delta$ Cephei, $\eta$ Aquilæ, and $\zeta$ Geminorum? Are they markedly less eccentric? Can they be inferred to be more spacious? No real discrimination may be possible, and if so, this line of search fails, and some other must be struck out. But it is clear that only tentative inquiries, pursued untiringly and successively, can avail to bring us nearer to the central truth we are in quest of.

The light-changes of stars are determinate in amount just in proportion as they are accurate in period. Irregularities of one kind are concomitant with irregularities of the other. They reach, in long-period variables, the limit of total disregard of traceable law. For one settled cause of variability a number of consilient causes would seem, in such objects, to be substituted. Should their co-operation break down—should one among them become temporarily ineffective—every vestige of cyclical recurrence may disappear. And it is important to note that stars with disturbed periods merge, by insensible degrees, into stars with no periods at all. Other stars show intermittent periodicity. They start cyclical variations only to drop them after a few recurrences, the alternations being often repeated at indefinitely prolonged intervals. A law of order is present; it has not been abrogated; but its

workings are almost neutralised by adverse influences. Then again, stars are found subject to uncertain accesses of light-change. Fits of instability of the most marked kind may be followed by long epochs of constancy, as in the case of P Cygni, and, perhaps we may add, of $\eta$ Carinæ; and many objects rejected from revised catalogues of variables as having failed to make good their title to inclusion are similarly stars reposing after more or less protracted crises of activity. The relations of stellar fluctuations to time are indeed unlimitedly various. They are, however, characterised by one feature which persists significantly, though far from immutably, notwithstanding the disguising effects, in Mira-variables, of accelerated, retarded, and duplicated phases. This is the more rapid increase than decrease of light. It is strongly pronounced in Cepheid and cluster variables; it asserts itself with modifications in variables of long period; in the sun it is never obliterated by the supervening irregularities of the spot-cycle. This wide range of agreement hints at some deep-seated principle of community, undefinable at present, and intangible to our mental grasp, yet lying at the root of the diverse phenomena of stellar light-change.

Their specific association with particular spectral types is a fact replete with meaning, no less than the exemption from variability, complete or partial, of whole classes of stars. Taking first the negative cases, we find the Wolf-Rayet family characterised by exceptional stability. Not one of its five-score members, so far discovered, shows the smallest symptom of luminous variation. Nor are their congeners, bright-line helium stars, ordinarily affected by it. Those that are so affected betray qualities in some way unusual. Among them are to be reckoned nearly all temporary stars, the singular short-period variable in Lyra, $\eta$ Carinæ, and P Cygni. Nebulous stars are not as a rule variable. The Pleiades shine with approximate constancy; the star-groups at the hearts of the great Orion and Trifid nebulæ give no conspicuous sign of fluctuation;[1] and isolated stars with nebular appurtenances are, for the most part, steady light-givers. T Tauri, however, makes an exception; and disappearances,

[1] The fifth and sixth stars of the trapezium have, however, certainly gained brightness of late. Comas Solà, *Astr. Nach.* No. 3751.

transient or lasting, of certain minute stellar denizens of planetary nebulæ have been, from time to time, asserted or surmised. White stars of either spectral variety are scarcely ever intrinsically variable. As spectroscopic doubles they are indeed subject to obscuration by eclipse; as telescopic doubles, to slight and capricious fluctuations in the magnitudes of one or both components, disconnected, apparently, from any of their orbital circumstances. Only three hydrogen or helium stars are known to be variable in any true sense; these are *u* Herculis, U Geminorum, and $R^2$ Cygni; and the rarity of this association of qualities makes it especially desirable that their spectral distinctions should be scrutinised with the utmost care. Very few second-type stars vary otherwise than extrinsically. Nor do they, that we yet know of, undergo eclipses. Yet many are binaries of the Cepheid kind, and thus become *compulsorily* variable. The solar quality of light must be regarded as highly favourable to steady radiation.

Just the reverse is true where banded absorption comes in. Stars of the third and fourth spectral types are not only pre-eminently variable, but they vary almost without exception irregularly, or in long periods. No spectroscopic binaries,[1] no Cepheid or Algol-stars have been found among them. In the character of their light-change, the two classes of stars with banded spectra are indistinguishable. But their spectroscopic study has brought into strong relief the different conditions of gaseous incandescence prevalent in each. In fourth-type stars it keeps aloof from fluctuations of brightness; the same vivid lines gleam in variables and non-variables; nor do they seem to kindle or fade in correspondence with the general light. Those that are visible in third-type stars, on the contrary, are an exclusive and unfailing mark of extensive variability, and attest, by a sympathetic course of development, their intimate connection with its processes. All this teaches us that the processes in question have their seat in limited regions, and are in a measure detached from the action going forward in other parts of the same stellar structures. Now variability of the kind prevalent in stars with banded spectra (as we know from

[1] The radial velocity of $\eta$ Geminorum proved variable on Campbell's examination in 1902. *Lick Bulletin*, No. 20.

certain of their spectral traits) originates in, or immediately above, the photosphere. Remote from the photosphere, accordingly, must be the location of the emitting gaseous strata in fourth-type stars, since the rays emanating from them shine undisturbed by the progress of the most conspicuous luminous vicissitudes. Hence the obvious deduction that these are conditioned by internal peculiarities. The brilliancy of stars depends, *cæteris paribus*, upon the rate of transport from within outward. Variability is an index to circulatory changes. In addition to this immediate cause, collateral influences doubtless come into play—forces which co-operate and combine, or mutually nullify one another, but so obscurely to us that there can be no profit, in the present state of knowledge, in prosecuting what could be no more than a conjectural inquiry.

# CHAPTER XXVII.

## IRREGULAR STAR CLUSTERS.

STARS associated together into communities are probably subject to mutual influences of special kinds. With the relative movements produced in them by the stress or pull of gravity we are not here concerned; they form an extraordinarily interesting subject for future inquiry, but as yet no hint of their method is derivable from the scanty materials at hand. The physics of clusters, however, falls within our scope, and is a topic more immediately accessible. It is open to discussion chiefly in two ways—by studying the spectral peculiarities, and the luminous variability of the component objects.

It is not always easy to distinguish between a casual "sprinkle" and a true cluster. The Pleiades are the only family of stars which shows a wandering tendency; the rest are *adscripti glebæ;* they have no common drift by which they could be set apart from casual inmates of the same sky-region. There remains the argument from probabilities of distribution, with its indefinite variations of conclusiveness according to the circumstances of each particular case. Yet it usually suffices for conviction. None, at least, of the five hundred registered clusters present any real ambiguity of character, although many other groups doubtless subsist unrecognised because poor in numbers and loosely scattered.

Two varieties of stellar collections can be readily discriminated. One is characterised by a spherical form; the constituent bright points press inward towards a centre; they aggregate into "globular clusters." Those termed "irregular" appear to be constructed on a different plan. Very slight traces of interior condensation are perceptible

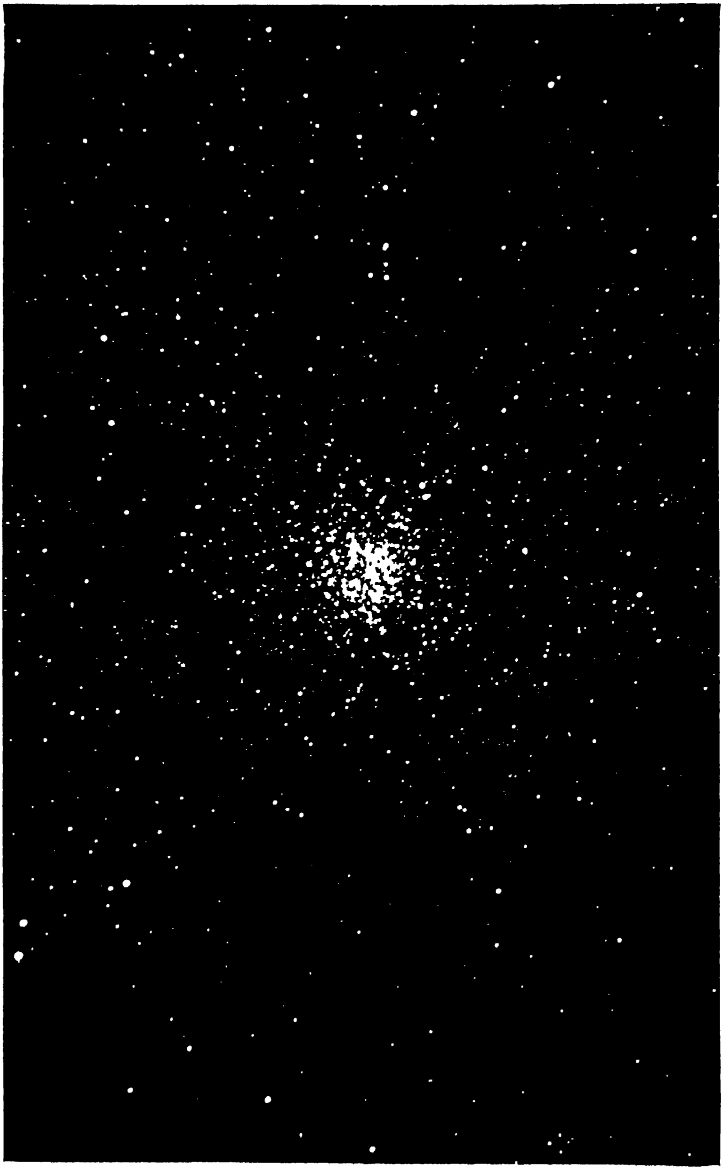
in them; they are made up of star streams, branches, and spirals, more or less closely intertwined and commingled. A glittering assemblage in Gemini (Messier 35) has an obviously radiated structure. Lord Rosse was struck with wonder at the arrangement into loops and arches of the stars in M 37, a similar object in Auriga. Still more definite and amazing are the "patterns, consisting of lines, wreaths, and curves of stars," in Dr. Roberts's photograph of a cluster in Cassiopeia (N.G.C. 7789), taken with an exposure of ninety minutes, 26th November 1892. The effect of a marshalled array is irresistible.

Interior vacancies seem correlative to a streaming conformation. They perhaps represent spots denuded of their bright inhabitants by the action of some unknown expulsive force. Irregular clusters, at any rate, are often remarkably perforated or furrowed. Some are rendered, by the development of "dark lanes," essentially bifid or trifid. The well-known star-throng in Antinous (M 11) is broken up by partial clearings in a manner suggestive of eventual disruption. The breaches in the masonry (so to speak) are finely shown in a photograph taken by Dr. Roberts, 10th August 1896, reproduced, by his kind permission, in Plate XIX. M. Fenet, from an earlier Crowborough plate, mapped 395 components of this cluster, which includes altogether about 1200, and remarked that most were entitled, by the close attendance of satellite-stars, to be regarded as forming multiple systems.[1] Their collection into seven or eight separate allotments was evident to him, and could not, he thought, fail to become further accentuated with time. All, nevertheless, yield apparent allegiance to a ninth-magnitude star, which fully sextuples the brightness of any of its followers. A spectroscopic examination of this object would be desirable. The general quality of its light might be readily ascertained, and the detection of motion-displacements need not be despaired of. A catalogue of two hundred members of this brilliant assemblage, referred to their leader, was drawn up in 1870 by F. R. Helmert, and compared with measures executed by Lamont in 1836-39.[2] The agreement was complete within the limits of

[1] *Bull. Société Astr. de France*, Mars 1895, p. 85.
[2] *Publicationen der Hamburger Sternwarte*, 1874, No. 1.

S.

P.



F.

N.

Photograph of Messier 11. Taken by Dr. Roberts with an exposure of 90ᵐ.

probable error; no discrepancies betrayed shiftings of relative position, although sure provision was made against their unnoticed occurrence in the future.

Helmert considered several of the stars observed by him to be slightly variable; but their changes made no show on the Arequipa plates of the cluster. Since, however, they were taken at an interval of a few days, only variables of short periods or rapid vicissitudes could have been disclosed, and none such, it is safe to say, are present. Yet there is some probability that a temporary member was added to the group upwards of sixty years ago. On the 12th of August 1839, Lamont entered No. 9 on his list as a "new star"; he had not perceived it before, and on the ensuing 9th of September it was gone. Helmert did not expressly look for it, but could only have missed seeing it through its extreme faintness.[1] Indeed, it was most likely, by that time, as hopelessly extinct as Nova Andromedæ now is. The stars of M 11, although devoid of nebulous attachments, are shown in one of Professor Barnard's small-scale photographs to form a knot at the margin of one of the great cloudy formations in the Milky Way, their actual nuclear relation to which he regards as "hardly questionable."[2] This may be; the supposition is plausible; yet it is a long way from being demonstrable. Meanwhile the practical inquiries to be made in connection with the cluster are these two: What is the spectrum of its leader star? and, Do any of its components vary in light?

The lovely double cluster in Perseus (N.G.C. 869, 884) resembles it in being non-nebulous, perhaps also in possessing galactic affinities. The twin groups are known respectively as *h* and $\chi$ Persei. Their connection is remote; dynamically they can scarcely be mutually dependent, but they are of closely analogous construction, and their components are similarly linked into festoons and spirals.[3] None of them can be perceived to drift, absolutely or relatively. This was put to the test in 1884, when 172 stars in "$\chi$ Persei" were photographically determined by O. Lohse for confrontation with

[1] *Publicationem der Hamburger Sternwarte*, p. 79.
[2] *Astroph. Journ.* vol. i. p. 11.
[3] Roberts, *Celestial Photographs*, vol. i. p. 39.

the results of Vogel's micrometrical measures of them fourteen years earlier.[1] Their seeming immobility will probably be maintained for many decades yet to come. Vogel's special catalogue of the thirty brightest among them (all above the tenth magnitude) might, nevertheless, usefully be revised, from the photometric point of view, for the purpose of detecting possible alterations of brilliancy. The task would be the more hopeful that some of the objects in question have a note of colour. A "ruby" star was allotted a central position in $\chi$ Persei by Sir John Herschel;[2] the Parsonstown reflectors displayed rosy, yellow, and bluish tints in many of its sparkling associates; and Mr. Espin, much more recently, located in the outskirts of the cluster eight reddish stars with fluted spectra.[3] These may be expected to prove more or less variable, though not in the prompt and definite fashion prevalent in globular assemblages.

Professor Barnard recognises two varieties of irregular clusters—the purely stellar and the nebulously stellar.[4] They can be distinguished with certainty only by chemical means. Long photographic exposures are needed to test satisfactorily the condition of grouped stars. The characteristic nebulosity of many clusters may in fact be counted one of the most important discoveries made with the assistance of the camera. But at present we are dealing with the non-nebulous kind, such as the Hyades and Præsepe in Cancer.

Aldebaran, the great red "eye of the Bull," is in, but not of the Hyades. The disconnection will be rendered obvious, and the relative drift more precisely definable, when the radial movements of the several stars can be spectroscopically fixed. This, indeed, is already feasible, were it not that the great telescopes of the world are otherwise occupied.

Forty-five stars in Præsepe have been located with rigid accuracy. Winnecke's observations of them in 1858, Asaph Hall's in 1870, above all, Schur's Catalogue for 1875,[5]

[1] *Der Sternhaufen $\chi$ Persei*, 1878, p. 30.

[2] *Phil. Trans.* vol. cxxiii. p. 373.

[3] Webb, *Cel. Objects*, ed. Espin, vol. ii. p. 200.

[4] *Astr. and Astrophysics*, vol. xiii. p. 180.

[5] *Astron. Mittheilungen der kön. Sternwarte zu Göttingen*, Th. iv.; see also Schlesinger's "Measurement of the Rutherfurd Photographs of the Præsepe Group," *Contributions from the Columbia University*, No. 15, 1898.

laboriously constructed from a triangulation with the Göttingen heliometer, ensure the detection of their future movements. They are extremely minute. In the course of thirty-two years they produced effects so small as to be barely determinable. The spectra of ninety members of this stellar family were photographed in or about the year 1896 at Harvard College.[1] Owing to their faintness— they ranged from 6·5 to 9·5 magnitude—the details of their classification remained uncertain; but the one main fact was brought out that the collection is of mixed quality. It does not seem to be expressly assorted in any way; no spectral pattern can be called predominant. Twenty-eight of the ninety associates were recorded as Sirian, sixty-one as solar or intermediate stars, and the third type was represented by a solitary specimen; that is to say, the percentage of first-type spectra in Præsepe is thirty-one, while it rises to sixty-five in the Pleiades, and sinks to fifteen in Coma Berenices. In this last asterism, however, the stars, although crowded, are not *clustered*.[2] Yet their crowding obtains significance through Professor Pickering's notice of their almost exclusively solar character.

A spectrographic survey, carried out at Harvard College, of four southern clusters of the coarse-grained or irregular description, has lifted another corner of the veil from this department of astrophysics. One of these objects, still uncatalogued, is situated in the neighbourhood of $\eta$ Carinæ; a second (N.G.C. 3523) is not far off; the third and fourth (N.G.C. 6405 and 6475 = M 6, M 7) are found in Scorpio. The plates exposed showed in the aggregate 705 spectra capable of characterisation, of which 576 were unmistakably of the first type.[3] The average proportion, then, of hydrogen stars in these four clusters is 82 per cent. Half a dozen helium stars were identified in the anonymous group, none in the rest. On the whole, spectral uniformity may be considered the ideal state towards which most clusters tend; it would perhaps, if accidental components could be eliminated, prove to be more nearly realised than it seems. In this connection it is of interest to note that M 37 in Auriga consists

[1] *Harvard Annals*, vol. xxvi. pt. ii. p. 264.

[2] W. O. Kretz, *Contributions from the Columbia University*, No. 16, 1900, p. 478.

[3] *Harvard Annals*, vol. xxvi. p. 283.

wholly of yellow stars, presumably belonging to the solar class. The sky, in Admiral Smyth's phrase, appears in that spot as if strewn with gold dust. The companion cluster in Gemini is, on the other hand, resplendently white; and Dunlop registered at Paramatta a bluish globular cluster (N.G.C. 6723) likely to be packed with Sirian stars.

The jewel-cluster about $\kappa$ Crucis is differently organised. Harmonies of contrast rather than of consonance may here be observed; but the collected brilliants display their various tints effectively only in the fields of large telescopes. From measures of 130 of them, Mr. Russell of Sydney derived in 1872 ostensible evidence of comparatively rapid interstitial movements during the thirty-five years elapsed since the date of Sir John Herschel's corresponding work; but until a fresh set of determinations gives assurance that they are pursued systematically, little weight can be laid upon discrepancies otherwise explicable. His suspicions of variability in twenty-five components have not so far been verified. Several are bright enough to show distinctive spectra, the nature of which it would be particularly interesting to ascertain. This beautiful object lies near the northern border of the "Coal Sack."

Irregular clusters obviously form systems of extreme intricacy. They cannot be pieces of mechanism set in action by some uniformly operating motive power. Their aspect is in most cases irreconcilable with the hypothesis of a dynamical equilibrium. Few, if any, betray by movement or conformation the influence of a preponderating centre of attraction. They rather suggest inconceivably complex aggregations of partial systems bound together loosely nor perhaps indissolubly. The investigation of their mutual relations will tax the resources of the old as well as of the new astronomy. Some of the problems to be confronted have just begun to take shape, others loom on a remote horizon. As a prelude to dealing with them, the separation might gradually be effected of the really physical from the merely optical components of clusters. The process will be greatly facilitated by the ready help of the camera; and the slow evolution of telescopic or tangential displacements can already in part be forestalled by the spectroscopic disclosure of radial velocities.

# CHAPTER XXVIII.

## NEBULOUS CLUSTERS—THE PLEIADES.

"TANGLED in a silver braid" of shining world-stuff, the Pleiades stand out as the typical nebulous cluster. They give signs of not being indefinitely remote. The assembled stars have a common drift, which is most likely a perspective effect of the sun's advance in the opposite direction. If this be so, their light spends just 200 years in reaching the earth, the rate of our progress towards the constellation Lyra being taken at twelve miles a second. Alcyone then radiates at the very least 190 times more powerfully than our sun; in its place, Sirius would appear fainter than the fifth magnitude; it would be outshone, not only by the *lucida* of the group, but also by five of its companions—by Atlas, Merope, Electra, Maia, and Taygeta. Thus the glory of the Atlantids would be but slightly enhanced by the addition of the great Dog star to their number, and the scale of the system must be commensurate with the magnificent luminosity of its members.

A beginning has been made in the discrimination of the genuine Pleiades from their optical companions. The definite character of their proper motions has made actually feasible what in other similar collections is only remotely possible. The outcome of Elkin's measures with the Yale heliometer in 1884-85[1] was to distinguish forty-five stars, including Alcyone, as inseparable travellers, while eight proved their independence by dropping out of the ranks. This group of forty-five members may be regarded as a nucleus round which additional stars will aggregate as their movements develop.

[1] *Transactions Yale Observatory*, vol. i. pt. i. 1887.

How far it will extend, how many of the small stars swarming on long-exposed negatives it will eventually take in, remains conjectural. Its delimitation, however, should be practicable in the course of a decade or two; for the comparison of photographs taken about 1915 with those of 1885 and 1888 may be expected to bring numerously into view relative displacements consequent upon the abandonment, as it were in mid-ocean, of a multitude of pseudo-Pleiades exempt from the drift belonging to the true cluster. There is reason to think that this process of expulsion will have to be carried far. The self-selected assemblage will probably not be over-crowded. Exact numerical inquiry has led to many unexpected results, but to none more surprising than that of the thinning-out of faint stars within the area of the Pleiades. Professor Bailey counted nearly 4000 on a photograph including it taken with the Bruce twenty-four-inch lens in 1897; but their density, as a detailed examination made evident, fell off notably and systematically inside the precincts of the system. "It therefore appears," Professor Pickering wrote,[1] "that the total number of stars in the region of the Pleiades is actually less than in adjacent portions of the sky of equal area, and it is much less than the corresponding number in many parts of the Milky Way." Regarded, then, as a physical entity, the cluster includes only the brightest of the spangled points thrown together into the field. The spangles of the background would indeed presumably be still more numerous but for the absorbent effect of the nebulous masses attached to the brilliant stars in front of them. Their paucity, at least, must be somehow accounted for, and this explanation of it, suggested by Professor Pickering, seems admissible. M. Stratonoff,[2] too, was led, by a study of stellar distribution in their neighbourhood, to the conclusion that the physical associates of Alcyone are comparatively few; and the conclusion is the more interesting from the sure prospect of bringing its truth to the test.

The Pleiades might be described as not merely a nebulous cluster, but as a cluster of nebulæ, so numerous and so sharply characterised are the cloudy forms collected within its borders. All save one are photographic revelations. The exception is the "Merope nebula," discovered by Tempel 19th October

[1] *Astroph. Journ.* vol. v. p. 352. [2] *Astr. Nach.* No. 3441.

1859. A mere "breath stain" on the sky, it is, to telescopic vision, a highly elusive object; yet it is always there, striated and definite, when looked for by chemical means, and the hypothesis of its variability has long ago been abandoned. The Maia nebula has something of the same striped aspect, but clings in a strongly curved whorl to the star which forms its nucleus. Mr. H. C. Wilson of the Goodsell Observatory described as follows a photograph of this object taken by him 30th January 1894.[1] "The region about Maia is especially interesting. A very bright horn-shaped patch of nebula runs out from the west edge of the star-image immediately northward, and extends to a distance of 3′ north of the star. The nebula here is full of irregularly parallel streaks similar to those about Merope, but making only a very small angle with the meridian. Some of them run to and beyond the bright stars north of Maia. A series of rather broad and diffuse patches extend from the middle of the group on a diagonal toward the north-west, reaching to a comparatively bright pair of stars in that direction."

A second Merope nebula, totally unlike the first, was discovered by Professor Barnard with the Lick thirty-six-inch refractor 14th November 1890.[2] It is round, clearly terminated, and centrally condensed, 30″ in diameter, and presents the general effect of a distant comet. With the adjacent star it forms so close a combination as to indicate, almost of necessity, the slow progress of mutual revolution. Mr. Burnham, who measured the new nebula at Lick in the autumn of 1891, regarded it as "one of the most singular objects in the heavens," and "unique with respect to its nearness to a bright naked-eye star."[3] It is the brightest nebula in the Pleiades, and came out well on plates taken by Professor Keeler in 1898 with the Crossley reflector.[4]

Another cosmic species singularly exemplified in this cluster might be called "ribbon nebulæ." They run in narrow, straight bands from star to star, in one case stringing together six or seven, "like beads on a rosary," and they pursue with

[1] *Astronomy and Astrophysics*, vol. xiii. p. 193.
[2] *Astr. Nach.* Nos. 3018, 3032.
[3] *Ibid.* No. 3074; *Publ. Lick Observatory*, vol. ii. p. 174.
[4] *Journ. Brit. Astr. Assoc.* vol. ix. p. 133.

fair accuracy, along parallel lines, an east and west direction. What manner of communication they establish between the suns they connect it is impossible to divine. They may conceivably be mere survivals of a prior order of things, belonging rather to the past than to the present; but no structures more curious have been brought to our notice by the camera than these long, luminous highways built as if for the purpose of facilitating intercourse between the cities of space. An *unfinished road* starts from Electra towards Alcyone; it has been completed over only about one-third of the way. Or is it the wreck of a celestial causeway which formerly reached its destination, but has been gradually, for some ages past, falling out of use and repair? The question is a daring one; ultimately, however, the comparative study of analogous objects may supply hints for answering it, at least by a plausible surmise. The cluster is besides crowded, especially in the neighbourhood of Alcyone, with irregular or nondescript nebulæ, which choke the background as if with rolling fog. But in general the tendency is unmistakable to assume filamentous shapes, such as were shown with peculiar distinctness in two photographs taken by M. Stratonoff at Tashkent early in 1896 with multiple exposures of respectively ten and seventeen and a half hours.[1]

The history of the Pleiades nebulosities does not end here. Professor Barnard had long been aware of a dulling of the sky-ground over a vast adjacent area; and at last, in December 1893, he put these vague perceptions to the test by means of a ten hours' exposure with the Willard lens.[2] "The resulting picture," he wrote, "showed a number of singular curved and streaky nebulosities, apparently connected with the Pleiades and extending all about the group." Some of them he was able to trace for several degrees on either side, especially towards the east. Yet doubts were expressed as to whether spurious photographic effects were not in question. The phenomenon disclosed was, indeed, so amazing that some degree of scepticism was excusable. Its reality, nevertheless, had to be admitted. Confirmatory photographs were produced by Dr. Max Wolf,[3] by

[1] *Astr. Nach.* No. 3441. [2] *Ibid.* No. 3253; *Monthly Notices*, vol. lx. p. 258.

[3] *Astr. Nach.* No. 3275; *Sirius*, 1891, p. 106. Wolf's photographs were taken previously, but interpreted subsequently to Barnard's.

Mr. H. C. Wilson,[1] and by Professor Bailey. A skilful drawing by Mr. E. Calvert, embodying the combined results, is reproduced in Fig. 46. But its limits are too narrow to include

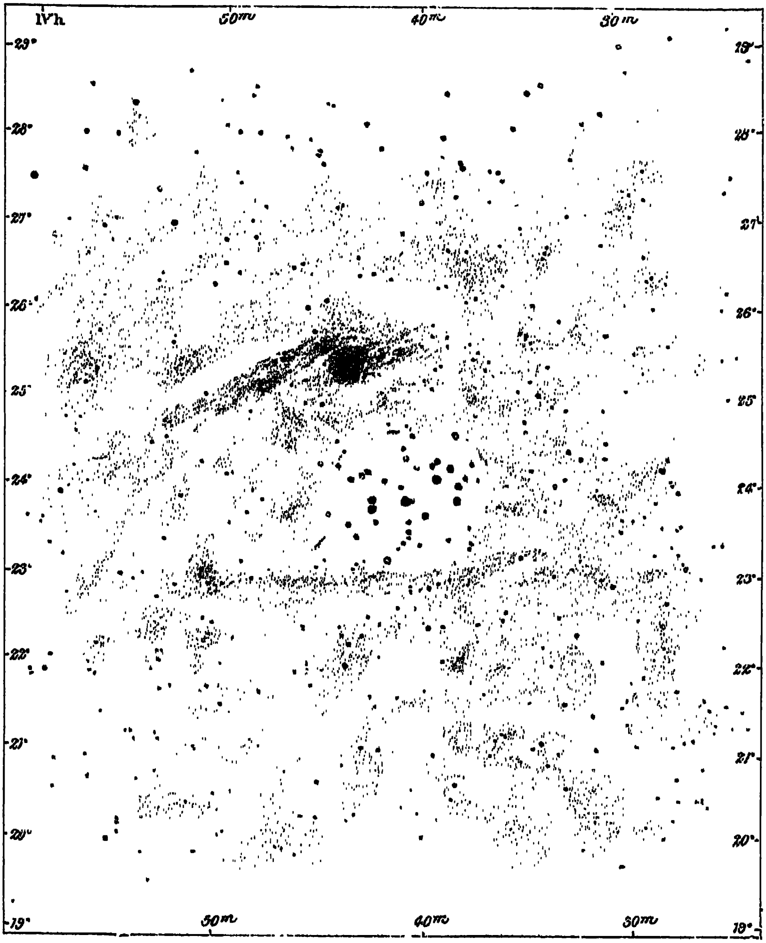



FIG. 46.—Drawn from Photographs by E. Calvert.

the whole of these far-spreading formations. There seems no end to them. The interior nebulosities are left undepicted for the sake of clearness. We are thus brought face to face

[1] *Pop. Astr.* Feb. 1899.

with the "startling fact" (as Professor Barnard calls it) "that the Pleiades and their involved nebulosities are but the central condensation of an enormous nebula, intricate in details, and covering at least a hundred square degrees of the sky."[1] The magnitude of this mixed system staggers belief and confounds the imagination. We contemplate it with imperfect apprehension of its scope and significance. For the present, the relations between its various parts appear scarcely open to investigation. The possibility even of speculating upon them will offer itself only when acquaintance begins to be made with the spectral characteristics of the Pleiades nebulæ. That they are all alike gaseous may safely be assumed; nevertheless, their dispersed light, when it becomes practicable to examine it, will perhaps offer diversities full of interest.

Among the stars of the cluster a single spectral type markedly predominates. It may be distinguished as "late Orion." Hydrogen absorption is prominent; helium absorption also asserts itself, but with less emphasis than in the earlier stars of the same class.[2] This quality of light is common to all the principal stars; those that deviate from it are of inferior grades of brightness, and may eventually, through the effects of proper motion, be sifted out from an assemblage to which they do not properly belong. Hence, when the group comes to be organised on a definitive basis, the *gross* percentage of sixty-five helium stars may have to be raised very much higher. The first example of a mixed hydrogen series was met with in Alcyone. Professor Campbell was astonished to perceive in 1893 that its spectrum, otherwise marked only by absorptive action, included a glowing crimson C. Very remarkably, too, this solitary bright ray is coupled with a dark streak, situated, as usual in cases of duplication, on its more refrangible side. Which is the displaced line has still to be ascertained. Pleione, the only other member of the family showing signs of emission, is spectroscopically akin to $\gamma$ Cassiopeiæ. Its bright rays bisect obscure bands.[3] The recession at the rate of eight or ten miles a second of the solar from the Atlantid system must occasion a perceptible shift towards the red of all the spectral lines of its members, to which constant

[1] *Monthly Notices*, vol. lx. p. 259.

[2] A. C. Maury, *Harvard Annals*, vol. xxviii. p. 20.

[3] See *ante*, p. 230

element are superadded the varied, and perhaps varying effects of their individual motions. Spectrographic researches hold out, then, the best prospect of gaining, within a reasonable lapse of time, some insight into the working of this amazing piece of celestial mechanics. From a triangulation, executed with the Göttingen heliometer in 1889-91, Dr. Ambronn derived, as he thought, indications of a division of the cluster into several distinct parcels of mutually dependent masses;[1] but his measures, which included only sixteen stars, had too restricted a scope to be decisive of much.

No stars of assured variability, whether periodical or irregular, are found among the Pleiades. Yet light-changes, eluding definite recognition, are suspected to progress. Maia and Merope have both been held to fluctuate slowly; and Atlas, divided into a pair by Struve in 1827, is now single, with all powers, in the serenest skies. Only a twofold occultation, noted by Hartwig in 1876, seemed to intimate the obscure survival of the vanished companion. Possibly it may make itself *felt* spectroscopically, even should it never again be seen. The motion-displacements, accordingly, yielded by Atlas deserve attentive scrutiny, since from them may be obtained the key to one of the long outstanding enigmas of double-star astronomy. Another member of the group appears to have an authentically variable attendant. In Wolf's map of 1874 an anonymous 7·2 magnitude star due south of Alcyone is marked as a wide double; it was single in the Paris photograph of 1886, but again double in that of 1888, when the satellite had risen to eighth-magnitude brightness. Yet M. Chevremont, reviewing the collection with a small refractor in November 1895, could find no trace of it.[2] This was the most precisely defined among several cases of presumable light-fluctuation met with in the course of his survey. Again, M.M. Müller and Kempf constructed at Potsdam in 1899 a photometric catalogue of ninety-six Pleiades,[3] forty-two of which, given in the Bonn Durchmusterung as of 9·5 magnitude, seemed to have diminished so considerably in

[1] *Astr. Mittheilungen*, Th. iii.; quoted in *Observatory*, vol. xvii. p. 309.

[2] *Bull. Société Astr. de France*, 1896, p. 293.

[3] *Astr. Nach.* Nos. 3587, 3588.

brightness that their mean magnitude could not be placed higher than 10·7.[1] Very little real change, however, may here have been concerned, since the ordering of stars in the lower ranks of the Durchmusterung is known to have been a highly casual process. It can scarcely be doubted, indeed, that some components of the cluster are, in a measure, variable, but their variability is of a kind not easily certified; it follows no method; it obeys no time-prescription; its effects, perceived when least looked for, cannot be counted upon to recur. Hence the problems of light-change set by the Pleiades are of a peculiarly baffling nature.

[1] Vogel, *Jahresbericht*, 1899.

## CHAPTER XXIX.

### NEBULOUS CLUSTERS—*Continued.*

MANY nebulous clusters besides the Pleiades are known, but none in which the relations of stars and nebulæ are so highly specialised. In general, the stellar collection seems as if independently organised, and plunged as a whole into an ocean of cosmic fog, without any strong tendency on the part of its members to form individual nebulous attachments or connections. When, however, the structural details of such formations come more fully to our acquaintance, they may be found to contain evidence of a closer association between particular objects of the two species than can at present be vouched for. Such investigations can be conducted effectively only by photographic means and with carefully adapted instruments. For the purpose of bringing out the full extent of the nebulosity, small portrait-lenses have prerogatives, illustrated practically by Professor Barnard,[1] theoretically by Professor Wadsworth.[2] But pictures on a larger scale than those obtained with them are needed for the disclosure of many topographical minutiæ huddled together by the strong concentration due to their short focal length. For securing those, reflectors of powerful light-grasp are unsurpassable. Thus two lines of photographic inquiry should be made to converge upon nebulous clusters; one directed towards determining the limits of the involving nebulosity, the other towards ascertaining its constructive peculiarities.

To a superficial view the object we are now about to describe seems more like a cluster and nebula than a nebulous cluster. The nebula is "Messier 8"; it is just visible to the

[1] *Monthly Notices*, vol. lvii. p. 16.  [2] *Knowledge*, vol. xx. p. 194.

naked eye, and from the oval vacancies which interrupt its light, it has received the descriptive designation of the "Lagoon Nebula."[1] The cluster—separately catalogued as N.G.C. 6530—immediately follows it on the same parallel, but not in complete detachment. The two formations unmistakably overlap, and, to discerning vision, inextricably intermingle. Professor Barnard's negatives, taken with the Willard lens in 1892, showed the compound object to be "a singular mixture of stars and nebulosity. East and west its diameter is about 45′, and north and south some 42′. The southern side is sharply defined and serrated, with three distinct pointed projections. From its north-following corner a wisp of nebulosity extends nearly to a group of nebulous stars, and possibly with a longer exposure would be found to connect with them."[2] A picture on so small a scale could teach little regarding internal structure; the "lagoons," in fact, appear in it nearly *silted up* with diffused nebulosity. Many of the brighter stars are involved in the pervasive haze, and one in particular occupies too critical a position at the edge of "a very black hole" for the supposition of a mere chance arrangement to be permissible. It may be doubted, however, whether the 5·7 magnitude star, 9 Sagittarii, has more than an optical connection with the cluster, and the multitude of stellar points glittering in the background will almost certainly be separated from it by the slow discrimination of drifting movement. A preliminary step towards applying the test was taken by M. Comas Solà in 1898.[3] His photographic triangulation of the group fixes a starting-point for comparative inquiries which can yield tangible results only in the distant future. His plates showed the stars to be doubly implicated with nebulosity. One of the seventh magnitude acts as the focus to a cloudy mass, distinct, apparently, from a diffuse, elongated structure projected upon the central parts of the cluster, which it not impossibly encloses in annular folds.[4] The Lagoon Nebula gives a spectrum of bright lines. It will

[1] Clerke, *System of the Stars*, p. 284.

[2] *Astr. Nach.* No. 3111; *Astr. and Astrophysics*, vol. xiii. p. 792.

[3] *Astr. Nach.* No. 3585.

[4] Cf. photographs of the cluster and nebula by Naegamvala, *Knowledge*, vol. xix. p. 183, and by Roberts, *ibid.* vol. xxiii. p. 132.

be interesting to learn whether they are displaced by motion, and whether, if so, corresponding spectral shifts in the clustered stars ratify the presumption of organic relationship between the two orders of formation.

The optical history of nebulous objects is often curious and instructive. As an open cluster, N.G.C. 2239, in Monoceros, was first observed by Sir John Herschel. An adjacent patch of nebulosity, seen by Swift in 1865,[1] again attracted Barnard's attention in 1883. It proved to be a kind of knot on a great nebulous ring discerned by the latter in its entirety with the Lick twelve-inch refractor in 1889.[2] This encloses the star group like a ring-fence, and may be said to osculate with a second great filmy ellipse, of which only a section is perceptible. Then came the turn of the camera. Professor Barnard obtained a photograph of the complex arrangement 9th January 1894, which confirmed visual impressions while demonstrating their inadequacy. They were not misleading, but extremely partial. The photographed nebula is, in Professor Barnard's words, "about one degree in diameter, and very irregular in brightness and outline."[3] It involves the cluster with unequal condensations, which are especially heavy north of the bright stars. The nebulous knots, and the section of a large ellipse, fully depicted in the sketch of 1889, reappeared in the chemical picture. In this, the only effect of annularity left visible is that a vacant interior space seems reserved for the conspicuously grouped stars. Their chief being of the eighth magnitude, the determination of its spectral character should present no difficulty, and would be of particular value as a test of nebulous affinity.

The number of alternative titles by which the star catalogued by Flamsteed as "15 Monocerotis" is known expresses the curious variety of its claims to distinction. It is variable, multiple, and nebulous. In the first capacity it is designated "S Monocerotis." Its fluctuations from 4·9 to 5·4 magnitude, in a period of $3^d\ 10^h\ 38^m$, were noted by Winnecke in 1867. These elements are indeed still somewhat uncertain. They need verification and revision. The

[1] *Sidereal Messenger*, vol. ix. p. 47.

[2] *Astr. Nach.* No. 2918 ; *Astr. and Astrophysics*, vol. xiii. p. 178.

[3] *Ibid.* p. 643.

variable is, moreover, the leading member of a triple combination, enrolled by Struve as "Σ 950." With a green companion at 2·8″, and a bluish one at 16·6″, it makes an exquisite telescopic object, but gives no sign of orbital motion. It occupies a dominating position in a collection of fifty or sixty stars, ranging from the eighth to the thirteenth magnitude, one of which is subject to fits and starts of extensive variation.[1] By virtue then of its chiefship of a cluster, 15 Monocerotis is registered among nebulæ as N.G.C. 2264. Nor solely on this account. Both Sir John Herschel and Lord Rosse suspected it to be nebulous, and Bruno Peter, who measured forty-five components of the group at Leipzig in 1879-82,[2] found their leader visibly wrapt in a hazy envelope. But the wide extent of its nebulous connections was entirely a photographic revelation. A picture of the region about 15 Monocerotis, taken by Professor Barnard on 1st February 1894,[3] showed it to be involved in a great nebula some three degrees in diameter. "It clusters densely," he says, "about the groups of stars, and then spreads out in a weak, diffuse light, with rifts in it, and irregularly terminated along the edges of a vast vacancy in the Milky Way. The condensation, which is very strong, is not at 15 Monocerotis, but twelve minutes south-preceding that star, where it becomes a compact mass with numerous wisps and holes in it." The absence of nebulous concentration about the individual stars struck him forcibly, especially by contrast with the different state of things in the Pleiades.[4] The nebulosity is free and general; no single member of the stellar assemblage appropriates a special share, or carves from it an appendage of its own. Yet it is difficult to doubt that the apparent association is real and physical.

The Wolf-Rayet spectrum is, broadly speaking, reversed in that of 15 Monocerotis. It includes both the hydrogen series and the upper "blue" band; metallic lines scarcely appear, but those of oxygen, nitrogen, and silicon are unlikely to be absent. About the peculiarities of the less refrangible section nothing is yet known. Here, perhaps, symptoms of

[1] Gore, *Knowledge*, vol. xxii. p. 201.
[2] *Abhandl. der kön. Sächs. Ges.* Bd. xv. Th. i. 1889.
[3] Reproduced in *Knowledge*, vol. xix. p. 109.
[4] *Astr. and Astrophysics*, vol. xiii. p. 642.

emission will be found; indeed, a bright C might be looked for with success not only in 15 Monocerotis, but in some one or two of its principal associates.

An eighth-magnitude star in Auriga was noticed by Auwers about 1860 to be projected on a hazy disc (N.G.C. 2175). The object is placed centrally in a group of smaller stars, enveloped in nebulosity strongly manifested in Professor Barnard's photographs of 1894.[1] The combination is quite similar to that just described in Monoceros. The spectrum of N.G.C. 2175 was examined by Professor Keeler with an indecisive upshot.[2]

Sir John Herschel observed at the Cape "a very remarkable object" in the Milky Way, where it crosses the tail of Scorpio. It showed to him under the guise of "a decided, tolerably defined, semi-nebulous mass, with abundance of very small stars forming altogether a telescopic Magellanic cloud. It fills about a field, and has branches and sinuses."[3] This miniature Nubecula (N.G.C. 6437) invites photographic delineation. Long exposures may disclose in it constructive particulars of extreme interest.

Nebulous clusters are connected, by insensible gradations, with certain tracts of nebulosity in the Milky Way, which, since they are situated in, or in the line of sight with a stellar stratum, necessarily appear more or less densely star-strewn. The stars strewing them do not, however, collect into groups capable of individualisation; hence they cannot be termed "nebulous clusters." These suggest some kind of organisation; they are more or less isolated and coherent entities, and are distinguishable as such from layers and beds of stars, however closely packed. Not that a clear line separates the two kinds of formation; the multiplicity of the heavens is too great for this to be possible; but it is well to maintain differences ideally, even though they be blurred, here and there in the concrete, beyond our perplexed powers of recognition. Nebulous clusters, on the other hand, shade off, as their members become fewer, into nebulous groups such as the Orion Trapezium, and reduce, "in the limit," to simple nebulous stars. These will be the subject of a future chapter.

[1] *Astr. and Astrophysics*, vol. xiii. pp. 180, 182.

[2] *Publ. Lick Observatory*, vol. iii. p. 202.

[3] *Cape Results*, p. 115.

# CHAPTER XXX.

## GLOBULAR CLUSTERS.

THERE is no possibility of failing to recognise in a globular cluster a true agglomeration—a structure *teres atque rotundus.* The systemic unity of such objects is as evident as that of a "globe of dew," though it is by no means certain that they are not, like that "frail and fading sphere," in course of more or less speedy evaporation. A gradual process of ejection is at least suggested by their streaming edges and filamentous appendages, formed of branching rows of stars, apparently on the move outward. One hundred and ten globular clusters were registered by Sir John Herschel in 1864 in his "General Catalogue" of nebulæ, and not many have since been identified. They are astonishing constructions. Their silvery radiance is a delight to the eye; the imagination is allured by their visionary beauty; reason is startled by the recondite nature of the problems they intimate. What, we cannot but ask ourselves, is the true nature of these mysterious "balls of stars"?[1] Are the luminous particles composing them *suns* in the proper sense? What are their mutual relations? How did they originate? In what are they to eventuate? Can mechanical stability be claimed for them, or must they be supposed to form temporary societies undermined by forces tending towards dissolution? On all these points definite information is still lacking; but there is no reason to despair of its future provision, since the inclusion of globular clusters within the scope of organised research is of quite recent date, and knowledge respecting them is accordingly in a nascent stage.

[1] See *Knowledge*, vol. xxi. p. 279.

It may, however, safely be affirmed that their components are sun-like bodies — that they are spherical masses at an enormously high temperature, radiating into space by means of suitably adapted photospheric apparatus. Some are intensely actinic. They are much brighter chemically than visually. They hence presumably emit light mainly of the shorter wave-lengths, and are abnormally hot bodies. But the secret of their nature cannot be divined in our present ignorance of their spectroscopic peculiarities, and those of the individual star-points in clusters will long remain inaccessible. Their combined light, nevertheless, where it is concentrated into a "blaze" at the core, is capable of being effectually analysed with powerful instruments, and the determination of its quality is a *sine quâ non* for progress in this branch. Until this has been effected, there is no possibility of assigning to globular clusters their proper place in the celestial hierarchy.

The great southern agglomerations, ω Centauri and 47 Toucani, seem almost untouched by the wear and tear of time. They show few signs of dilapidation. No dusky rifts, no glades or clearings are perceptible in them; the subtraction of material (if it be going on) has made little progress; they are as yet well compacted to the centre. Nor is a flow of stars outward hinted at unless obscurely. They are *cleaner* at the edges than most objects of their class; tentacular appendages are wanting; their components are not visibly in marching order. This may mean that they have but newly arrived at their present state of being, and if so, their spectra should be of an early type. To the component stars, accordingly, a very low mean density may probably be attributed; their attractive power will prove small relatively to their light; the corresponding interstitial movements must be slow, and will be difficult of detection.

Just within the northern border of the Milky Way ω Centauri is visible to the naked eye as a hazy star of the fourth magnitude.[1] Telescopically it presents a grand aspect. Nothing more strikingly effective can be imagined than the transformation, by optical means, of a blurred light-spot into a glittering and multitudinous assemblage of separate suns. Nearly 6400 can be distinguished on sensitive plates, besides

[1] Bailey, *Astr. and Astrophysics*, vol. xii. p. 689.

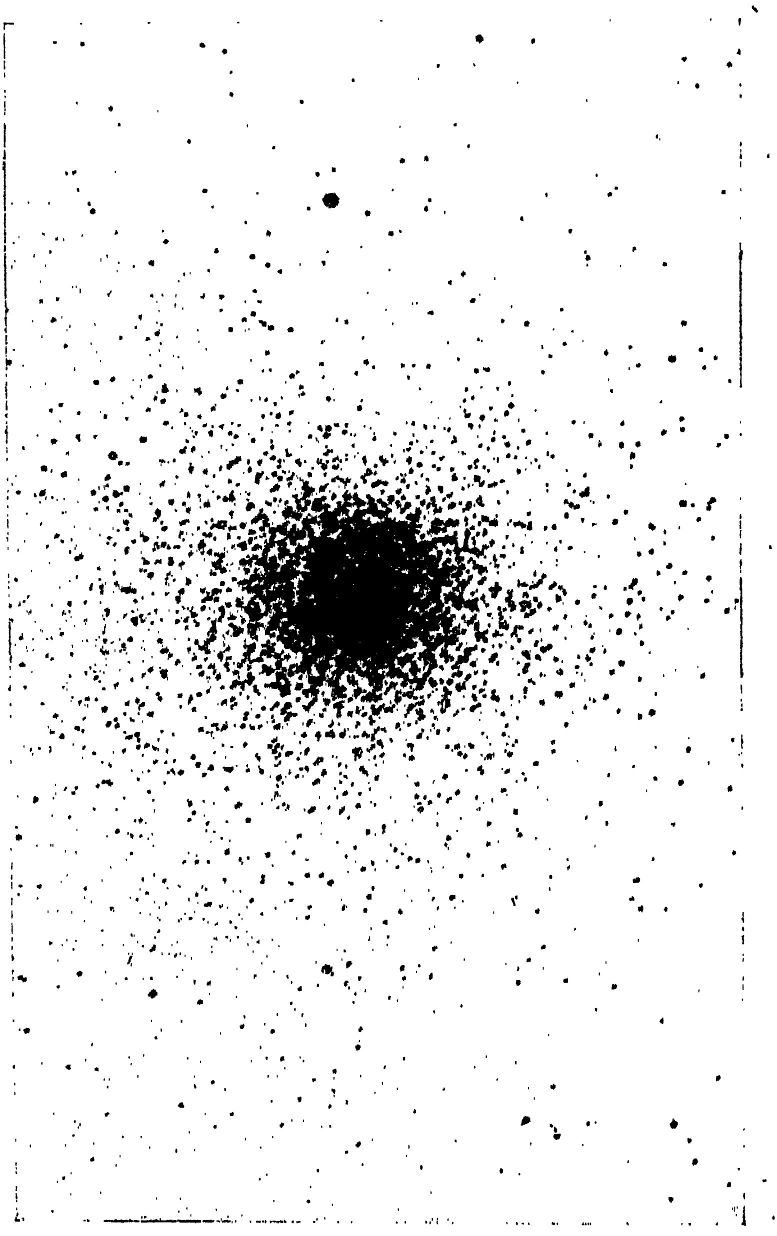


FIG. 47.—Photograph of ω Centauri (Bailey).

a crowd of others so small as to merge together into a grey mottling. No true nebulosity seems to be present. The photograph from which the counts were made by Professor and Mrs. Bailey is reproduced in Fig. 47. It was taken at Arequipa 19th May 1893 with an exposure of two hours in the thirteen-inch Boyden refractor. The area marked out for investigation covered 900 square minutes. It was "fairly well filled" with stars, and their statistical study defined the fact of their true central crowding.[1] They condense not merely in appearance, through the augmenting depth of spherical space in which they are distributed, but also as a consequence of actual compression inward. The number of stars per square minute was found, in fact, to increase in arithmetical progression with approach to the centre. Away from it the diminution ceased, a constant figure being reached along a line taken to be the boundary of the cluster; and this constant, since it must represent the areal population of the general sky, supplied a means of correcting the apparent results for that of the cluster. Deduction was accordingly made of 1616 unconnected stars, mere visual intruders from a limitless background; and there remained 5050 true components, collected within a circular space somewhat larger than that occupied by the full moon. They average about 12·5 magnitude.

The south polar cluster, 47 Toucani, is of equal loveliness with ω Centauri, although on a smaller scale. Its "computed diameter" is 22′[2]—that is to say, the *extra* stars which it projects upon the sphere die out completely at a distance of 11′ from its centre. They number about 2300, and are distributed in accordance with the same law noted as prevalent in the companion cluster. They are, however, even more densely aggregated; the realm is less spacious than ω Centauri proportionately to the throng of its inhabitants.

The great cluster in Hercules (M 13) presents a less uniform texture than its prototypes in the southern sky. Yet its constituent orbs follow virtually the same gradient of central compression.[3] Their distribution is affected besides by influences of an unimaginable kind. Three "dark lanes,"

[1] Pickering, *Harvard Annals*, vol. xxvi. p. 218.
[2] *Ibid.* p. 221. [3] *Ibid.* p. 220.

making an equiangular junction at a point south-east of the centre, were detected with the Rosse reflector in 1850.[1] An identical form of marking tends to recur in other parts of the cluster. On the Lick photographs of 1890-91, Professor Holden was able to trace no less than thirteen repetitions of it.[2] This insistence, he remarked in a local paper, made it evident "that a definite law was acting to produce this form, and that this law might be truly taken as representative for this cluster. In some way there are dark lanes produced and maintained among the hundreds of bright stars in this globular mass, and there are *many* such channels. How can we conceive of such a system? It is tolerably clear that either the dark lanes are absolutely empty of matter, or at least that they are empty of luminous matter." Yet neither of these alternatives seems to be in accord with fact.

A plate exposed during ten minutes with the Crossley reflector by Professor Keeler showed all the brighter stars in M 13.[3] Two hours were, however, needed to bring the swarms of their faint associates into view. In all, more than 5400 stars, fairly within the precincts of the cluster, were counted on a negative taken 13th July 1899. A study of their distribution, made by Mr. Palmer, Professor Keeler's assistant, elicited some noteworthy peculiarities.[4] The components separated, speaking broadly, into two distinct orders of brightness, those of intermediate magnitudes being comparatively scarce. Out of the total number of 5482 counted on the plate, 1016 were classed as bright, 4466 as faint, or below 13·5 magnitude. Now the mode of scattering of these two orders appeared sensibly different. That of the larger stars is radial—they extend outward in curved rows; that of their minute companions is more nearly globular. Moreover, the characteristic dusky tracks are vacant only as regards the former class of objects. They are lightly strewn with the diffusive star powder found everywhere in the cluster. To its presence Mr. Palmer attributes the effects of nebulosity noticed in earlier photographs. It requires a very high resolving power to distinguish the stellar haze created by flocks and

[1] *Phil. Trans.* vol. cli. p. 732.
[2] *Publ. Pacific Society*, vol. iii. p. 375.
[3] *Ibid.* No. 70, p. 201.
[4] *Astroph. Journ.* vol. x. p. 246.

throngs of sixteenth-magnitude stars from genuine "fluid haze"; but in this case there seems little doubt that the feat was performed. Confirmatory evidence of the best kind was afforded by Professor Barnard's direct observations with the forty-inch Yerkes refractor. They convinced him that globular clusters are non-nebulous formations.[1] Spectrographic impressions will probably before long add their testimony, at least in a negative sense.

With the thirteen-inch photographic refractor of the Potsdam Observatory, Dr. Scheiner obtained, 9th September 1891, the first plate of M 13 on which the stars were sufficiently defined for exact measurement.[2] He accordingly prepared a catalogue by which the places of 833 were fixed with the utmost accuracy; and these fundamental stars, henceforward kept under watch and ward, will perhaps one day disclose the plan of their movements, and thus enable future astronomers to attack, with some possibility of success, one of the most arduous problems in celestial dynamics. It confronts them, under a still more bewildering form, in a superb cluster in Scorpio (M 62 = N.G.C. 6266). Here a second focus of condensation is obvious; two star-globes are fused into one.[3] The contorted growth of a twin cherry may help us to realise, however imperfectly, the attendant indefinite complexity of the conflicting forces.

A compressed cluster in Serpens (M 5 = N.G.C. 5904), discovered by Kirch in 1702, presents telescopically the appearance of a softly radiant globe with divergent outliers. A photograph taken by Dr. Roberts 25th April 1892, indicated a nebulous interior; but no such effect came out on negatives exposed with Dr. Common's five-foot reflector, nor was it perceptible visually to Professor Barnard. It was due, presumably, to an amalgam of faint stars forming a kind of matrix for those bright enough to be individualised. The discovery of their variability was begun by Mr. Packer in 1890.[4] He remarked the fluctuations of two components,

[1] *Astroph. Journ.* vol. xii. p. 181.

[2] *Abhandl. der Kön. Preuss. Akad.* 1892, Anhang.

[3] J. Herschel, *Cape Results*, pp. 23, 113, Plate vi. Fig. 14.

[4] *Engl. Mechanic*, vol. li. p. 378; *Sidereal Messenger*, vols. ix. p. 380; x. p. 107.

and Dr. Common suspected many more to share the same character.[1] This premonition was followed up, though not until after five years, by Professor Bailey's announcement [2] that many globular clusters—say one in five—are veritable nests of variables. Their abundance is such that as many as a hundred—in Professor Barnard's words—"have been found in a space in the sky that would be covered by a pin's-head held at the distance of distinct vision."[3] Of 3000 components of ω Centauri examined within a radius of 22′, 128 were found to fluctuate to the extent of half a magnitude or more.[4] In one case a range of five magnitudes was observed; but that of most of the objects investigated was limited to one and a half, or two magnitudes. Very short periods are the rule; three are of less than seven hours; yet one is protracted to 475 days, and there will be a special interest in determining the nature of the light-change comprised in so long a cycle. A true "Mira variable" would seem an anomaly in a cluster made up of silvery white stars; since we are taught by experience to associate periods of many months with strong absorption and consequent redness of colour. But cluster-variables belong, for the most part, to a type apart, the character of which has been described in an earlier chapter. They have long minima, and brief maxima attained with extraordinary rapidity. The activity of their changes, when they set in, contrasts singularly with the completeness of their suspension during the intervals of rest. There is an entire absence of concert among the affected stars. Each is an independent, self-regulated phenomenon. No more curious spectacle is afforded by the heavens than that of a throng of seeming signal-lights waxing and waning every few hours under the sway, obviously, of some common law, yet with no trace of unanimity; some fading while their neighbours are on the rise, others stationary and semi-extinct, though only biding their time to enter upon a phase of renewed brilliancy; and none deviating by a hair's-breadth from the course of change individually prescribed for it.

[1] *Monthly Notices*, vol. l. p. 517.

[2] *Astroph. Journ.* vol. ii. p. 321; *Harvard Annals*, vol. xxxviii., contains a complete discussion of these variables by Bailey.

[3] *Address on Astronomical Photography*, p. 26; *Knowledge*, vol. xxi. p. 280 (Clerke).

[4] *Harvard Circular*, No. 33.

Eighty-five variable stars have up to the present been recognised in Messier 5, and they agree, for the most part, quite closely in a mode of fluctuation elucidated by Professor Bailey's persevering inquiries.[1] The form of their typical light-curve is not different from that assignable to the components of $\omega$ Centauri; but they tend unmistakably to obey a common period of approximately twelve hours, and the oscillations of nearly all are between the fourteenth and the fifteenth magnitudes.[2] Yet they are not executed simultaneously; a congruity of epochs is not even distantly indicated. Professor Barnard took visual charge in 1898 of some half a dozen of these strange objects,[3] and his list included Packer's original variables, Nos. 42 and 84 of the Harvard enumeration, stars exceptional in the great assemblage of which they form part, both as to the length of their periods and the manner of their change. This copies the pattern set by $\delta$ Cephei; it proceeds continuously, although not symmetrically, along a curve steep in its upward branch, sloping gradually downward, and interrupted by a "hump," significant of an abortive second maximum.[4] Its time-measure is about twenty-six days. Professor Barnard was struck with a number of ink-black holes rending the brilliant surface of the star-globe in Serpens. They are closely adjacent to the dense central portion, and suggest tunnelling operations on the scale of those progressing in the great Hercules cluster.

A cluster in Canes Venatici (M 3 = N.G.C. 5272) is similarly perforated. Lord Rosse observed "several small dark holes" at its core, from which "rays run out on every side."[5] A "bifurcated dark lane" was, moreover, perceived in the northern segment of the nuclear "blaze." From which we can gather that the distribution of stars in M 3 is controlled by forces of the same nature as those ruling in M 13. Yet the two clusters are markedly differentiated as regards light-stability. That in Canes is already known to contain 132 variables; while in the Hercules group diligent

[1] *Astroph. Journ.* vol. x. p. 255.
[2] *Publ. Pacific Society*, No. 70, p. 210.
[3] *Astr. Nach.* No. 3519.
[4] Parkhurst, *Astr. Journ.* No. 482.
[5] *Trans. Royal Dublin Society*, vol. ii. p. 132.

inquiry has failed to certify the presence of more than two, its components actually shining much more steadily than the average of the stellar multitude outside its limits. Eighteen hundred stars were counted by M. Orbinsky from photographs of M 3 taken at Pulkowa in 1894,[1] and his measurement of their places will in the future supply a test of their relative mobility.

A starry sphere in Pegasus (M 15 = N.G.C. 7078) seemed nebulous in Dr. Roberts's photographs;[2] but they were perhaps clouded by stellar dust, not by true cosmical fog. Of 900 members of this collection examined at Harvard College, 51 proved variable. The proportion in Ihle's great cluster in Sagittarius (M 22 = N.G.C. 4424) is much smaller—16 to 1550; and only 10 among 600 stars tested for stability in M 2 gave responsive signs of fluctuation. This cluster, which is situated in Aquarius, might be the twin of that in Hercules plunged in a deeper depth of space.[3] The clusters ω Centauri and 47 Toucani, so much alike in other respects, deviate widely in the matter of variability. Periodical stars by the score occur, as we have seen, in the former stately assemblage; in the latter, only six have been registered, notwithstanding the most careful scrutiny. Whence the diversity? Professor Pickering[4] surmises that it depends upon the relation of a common plane of revolution to the line of sight. Each globular cluster would be, on this view, a system, the movements of which, whether axial or orbital, are conducted on the same level. And should this level happen to coincide with the visual ray, variability would result, either through the rotation of such components as possessed unequally luminous surfaces, or as a consequence of the eclipses of those provided with closely revolving satellites. Yet neither rationale of light-change can, without grave misgivings, be admitted. Suns with dusky hemispheres, or permanently spotted, may be treated as mathematical fictions. Nor is any evidence as yet forthcoming that genuine eclipse-stars ever find a habitat in clusters. Certainly none of the

[1] Bélopolsky, *Astr. Nach.* No. 3338.
[2] *Celestial Photographs*, vol. i. p. 119.
[3] Secchi, *Atti dell' Accad. Pont.* t. vii. p. 90, 1853.
[4] *Harvard Circular*, No. 33.

cluster-variables so far investigated can be accounted such.[1] That they are rapid binaries may be plausibly surmised, but they must be of the non-occulting sort. In eclipsing stars the maximum is essentially permanent; the minimum is accidental. In cluster-variables opposite conditions prevail. Habitually obscure, they brighten incidentally.

Professor Bailey's discovery throws open a spacious field of research. Each variable cluster might well claim a sentinel appointed for the exclusive following of the complex, elusive, and rapid changes which ceaselessly develop within its compass. In December 1901, 509 components of star-globes were reckoned as periodical. Every one of these is perhaps a system apart; every one has its peculiarities, the inner meaning of which can only be drawn out by sustained attention. Powerful instruments are, moreover, required. The objects in question lie near the limit of practicable observation; work upon them taxes modern resources to the utmost. Nor can the photographic method alone be relied on. Long exposures are needed to show the stars at all, and they can naturally give no more than the "mean magnitude" during the intervals they cover. But when these intervals bear a large proportion to the entire period of change, such coarse-grained data cannot satisfactorily represent the manner of its progress. The resulting light-curve, as Professor Bailey says,[2] is always smoothed down; and it is smoothed to the limit of a straight line, in the ultimate case of the exposure equalling the period of a star's variation. Hence the absolute necessity for supplementary visual determinations to fill out the peaks and corners rounded off by the camera. At the critical epoch, when the flash is being turned on, every minute counts. Estimates of brightness at the rate of ten or twelve an hour are not too numerous for the purpose of keeping guard over the swift alterations going forward. The hourly or two-hourly averages given on sensitive plates are wholly inadequate.

Two questions of fundamental interest present themselves in connection with the variability of clusters. Why, we must ask, are the stars in one globular assemblage luminously unstable, while in others, its strict analogues, they shine quite

[1] *Harvard Annals*, vol. xxxviii. p. 234.

[2] *Astroph. Journ.* vol. x. p. 263.

steadily? The contrast is not explained by any visible difference of constitution. Variability does not appear to come in at any particular stage of growth; it is not associated with a definite situation in the heavens; it does not characterise pierced and outworn globes preferentially to compact ones, or *vice versâ;* it can, in short, be correlated with no feature obvious to direct notice. It remains to be seen whether any spectroscopic peculiarity corresponds to it.

Again, the absence from, or extreme scarcity of Algol-stars in clusters occasions perplexity. We are led to believe that rapid variables are, in truth, binaries revolving in the light-period. But if so, the orbital planes of a certain proportion of them ought to pass through the earth, with the outcome of affording us the spectacle of so many occulting pairs. If these do not exist, we shall be forced to conclude that cluster-variables owe their punctuality to some other cause than the strict time-keeping of satellites.

One of the most signal services rendered by photography to astronomy has been in the facilities supplied by it for the measurement of star-clusters. The relative positions, especially of the components of compressed groups, can only with extreme difficulty be established by direct triangulations; while every negative taken of them fixes their configuration at a given epoch, and gives the means of determining its changes, should they occur. Thus the places of sixty-two stars in M 5, catalogued at Harvard College in 1897, were estimated by Professor Pickering to be of so high a degree of accuracy that annual displacements amounting to one-hundredth part of a second of arc can be detected by their comparison with results similarly obtained from plates taken a few years hence.[1] The foundations have then been laid for an extensive superstructure of knowledge, as regards both the physical and the dynamical condition of globular clusters; yet centuries may elapse before it becomes possible—in Kepler's phrase—to "think over again," with apprehensive minds, those wonderful "thoughts of God."

[1] *Harvard Annals*, vol. xxvi. p. 247.

## CHAPTER XXXI.

### WHITE NEBULÆ.

"WHITE nebulæ"—so called by Professor Young[1]—are those giving continuous spectra. They are in an immense majority. They are reckoned by thousands, or tens of thousands, gaseous nebulæ by the score. True, very little progress has been made with their actual spectroscopic examination, the faintness of their rays forming, in general, an insuperable obstacle to their analysis; but their shape and aspect supply indications, rarely misleading, as to the quality of their light. That of elliptical and spiral nebulæ is, to the best of our knowledge, always continuous; and with these may be classed the round, centrally-condensed objects which abound in every nebular region of the sky. Several other varieties of this great sidereal family might be indicated, but they are by comparison scantily represented, and have been but little investigated. The paragon of white nebulæ is the grand ellipse in Andromeda. No other is visible to the naked eye; it should be, judging by appearances, much the nearest to the earth of the whole tribe; its structure is splendidly definite, and profoundly significant; its spectrum shows peculiarities challenging inquiries which must be long-continued and arduous, but promise results of far-reaching importance. In January 1899 Dr. Scheiner,[2] employing a small spectrograph in combination with a mirror of nearly thirteen inches aperture, and only forty inches focus—an apparatus specially adapted for dealing to advantage with objects of extended surface—obtained in seven hours a legible

[1] *General Astronomy*, section 891.

[2] *Astr. Nach.* 3549; *Astroph. Journ.* vol. ix. p. 149.

spectrograph of the nebula. The indications gathered from it were of a most surprising kind. Dark rays were perceived to interrupt the continuous light, and they seemed to agree with the Fraunhofer lines in the solar spectrum. The Andromeda nebula was accordingly inferred to be a genuine cluster of solar stars; but this conclusion is very far from being securely established. No bright lines could be made out in the Potsdam photograph, but many have been *seen* at Tulse Hill.[1] On 13th November and 11th December 1897, when they were particularly distinct, approximate wave-lengths were assigned to six or seven, all of which fall near lines in the Wolf-Rayet stars. The reality of the coincidences cannot at present be pronounced upon; they are hinted at rather than asserted; but their verification would enforce an entire recasting of ideas as to the nature of white nebulæ.

A photograph of the Andromeda ellipse, taken by Dr. Roberts 10th October 1887, set the example, since extensively followed, of resolving into spirals, with the help of the camera, all sorts and conditions of nebulæ. It was, indeed, a memorable picture. The vast structure is shown in it and its successors[2] to be furrowed through and through by dark channels, or rather by a single continuous channel, winding in symmetrical convolutions in a left-handed direction from the compact nucleus outward to the dim, indefinite margin. Thus the nebula is not simply a concatenation of flat rings separated by vacant intervals; if it were, the problem of its construction would be less difficult; since the annular gaps might represent spaces cleared of their contents by exceptionally acute gravitational disturbance, while the ejection of matter along a spiral track belongs to a totally different order of phenomena, and implies the operation of laws scarcely yet brought within our ken.

The Andromeda nebula is presumably a round disc viewed obliquely. If so, the angle of its inclination is about 25°.[3] Remarkably enough, the nucleus does not share the elongation of the surrounding spires, as it should if it were no more than a flat condensation in their plane. Its outline

[1] *Atlas of Stellar Spectra*, p. 125.
[2] *Celestial Photographs*, vol. ii. p. 63.
[3] Scheiner, *Photographie der Gestirne*, p. 332.

is, on the contrary, circular,[1] and its true shape must be that of a globe. There is no probability that the innumerable stars strewing the formation have any physical connection with it. Two small nebulæ in its immediate neighbourhood, on the other hand, certainly belong to its system. The closer and brighter (M 32) was discovered by Le Gentil in 1749; the other, which is situated in a nearly opposite direction, by Caroline Herschel in 1783. Both can be seen with powerful telescopes to be included within the limits of the primary agglomeration.[2] Le Gentil's nebula, indeed, appeared on a Meudon negative to lie as a condensed knot upon one of its external spires,[3] and the companion object doubtless owns a similar origin. The latter is an oval, apparently amorphous mass; its longer axis is inclined 60° to that of the great nebula. The two satellites may eventually yield signs of orbital revolution; or the whole disc perhaps rotates as one piece, and they along with it; we cannot attempt to decide which condition is the more likely to prevail. Perhaps neither to the exclusion of the other. It is conceivable that the more remote member of the system circulates independently, while the inner companion is borne onward with the general swirl.

Far inferior to this "Ajax" among the nebulæ, although eminent among the "other Argives," is a large lenticular object in Cetus (N.G.C. 252), noticed by Caroline Herschel in 1783. Sir John Herschel[4] considered its "streaky and knotty" texture to denote resolvability into stars; but it came out instead as a fine spiral in a photograph taken by Dr. Roberts 25th December 1899, a reproduction of which is given, by his kind permission, in Plate XX. The whorls are evidently much foreshortened. They are studded, as Dr. Roberts remarks,[5] "with numerous condensations of a stellar character," while six ordinary stars are probably seen in projection upon them. Measures of their positions relative to each other and to exterior stars might serve, he adds, for the

[1] This is denied by M. Antoniadi, on the strength of an observation with the giant siderostat of Paris, 1st Sept. 1900 (*Knowledge*, vol. xxiii. p. 251).

[2] Swift, *Pop. Astr.* vol. i. p. 112.

[3] Rabourdin, *Cosmos*, 19 Fevrier 1898, p. 232.

[4] *Cape Results*, p. 53.

[5] *Knowledge*, vol. xxiii. p. 132.

detection of any movements, rotational or translational, by which the nebula may be affected. Its considerable south latitude brings it within the spectrographic domain of the Cape Observatory, and the McClean apparatus might be competent to obtain an impression of a spectrum sure to prove interesting, if only it can be made distinctly visible.

A nebulous "ray" in Ursa Major (M 82) was described by Lord Rosse as "a most extraordinary object, at least ten minutes of arc in length, and crossed by several dark bands."[1] These run obliquely to the axis, and give the nebula—as Mr. Ingall said—"a twisted appearance, like a distaff of flax.[2] It appears to possess two centres of condensation, which must lend no slight complexity to its internal economy. Each is perhaps the starting-point of a separate arrangement of luminous coils, but no fair view can be got of them; they are foreshortened into mere broken lines. The nebula, Dr. Roberts explains,[3] is presented to us "in section, and the upper and lower surfaces are very rugged." The divisions between the rings hence took shape in a negative, to which he gave three and a half hours' exposure, 31st March 1889, as "rifts and attenuated places" not obviously fitting together into a harmonious plan. The profile of a corrugated disc is not an easily intelligible object, and that is all that can be seen of M 82. Perspective has done its utmost to disguise its true aspect. Turned edgewise towards the earth, it betrays only by its indentations and rugosities the effects of the ploughing action to which for ages it has been subjected. Swift's "hair-line nebulæ" belong to the same category. They show as bare streaks of nebulosity, bulging a little where the nuclei protrude. Presumably they are flat, circular surfaces, the planes of which coincide with the line of sight.

The "ray" in Ursa Major is not solitary. It is placed at a distance of only 42′ from a larger structure (M 81), evidently of the same general character. The two were photographed together by Dr. Roberts in 1889, and cannot be wholly disconnected. The primary—if we may call it so—resembles the great Andromeda nebula, and, like it, was

[1] *Trans. Royal Dublin Society*, vol. ii. p. 79.
[2] *Engl. Mechanic*, vol. xlii. p. 311.
[3] *Celestial Photographs*, vol. i. p. 78.

Photograph of a Spiral Nebula in Cetus. Taken by Dr. Roberts, 25th December 1899.

resolved into a fine spiral. The spectra of both objects were found by Sir William Huggins to be continuous; but the significant details disguised by apparent continuity have still to be revealed.

The essential formative law of white nebulæ is unmistakably that of spirality. This conviction, strongly upheld by the long series of the Crowborough pictures, was irrefutably established by Professor Keeler's photographic survey with the Crossley reflector.[1] Owing to the strong light-collecting power of the instrument, the harvest of nebulæ garnered was so plentiful that the number within its reach over the whole heavens was estimated at no less than 120,000, and nearly all of these can be inferred, from the preliminary results obtained, to have a spiral shape. On the Lick plates, in fact, a small compact nebula, *not* disposed in luminous coils, stood out as a rarity. All spindle-nebulæ were resolved into spirals viewed aslant, but into spirals of various degrees of complexity. Some consist merely of two curved branches, shaped like the letter S, and diverging oppositely from a nuclear condensation. An object of the kind situated in Pegasus (N.G.C. 7479) is reproduced from Professor Keeler's photograph in Plate XXI. Subjoined are the drawings by J. Herschel, d'Arrest, Lord Rosse, and Tempel, with which Keeler compared the autograph picture. They make an instructive study. Herschel saw the object as a narrow spindle "extended between two stars," d'Arrest as a lozenge; Lord Rosse perceived, in addition, a mass of spiral convolutions surrounding a faint star, while Tempel caught the double effect of a round attached to an elongated patch of luminosity, but failed to discern their true connection. At last on the Lick plates the object disclosed itself under an intelligible aspect. "A glance at the photograph," Professor Keeler wrote,[2] "shows that the nebula is a two-branched, left-handed spiral, with a nucleus or condensation near the point of inflection. The preceding branch is strong and single, but the following branch is split into two, which cross where their curvature is greatest, at some distance from the centre of the spiral, and unite again at their extremities. This appearance in the components of the following branch, and the fact that

[1] *Astr. Nach.* No. 3601.

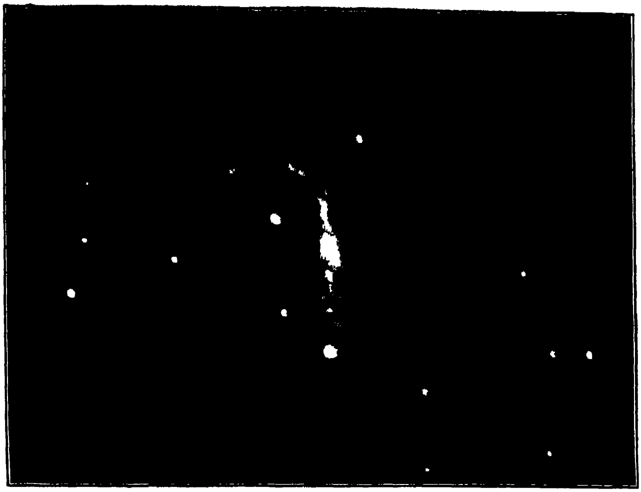
[2] *Astroph. Journ.* vol. xi. p. 3.

the ends of both branches curve around so as to approach the centre more closely than do the intermediate parts, are doubtless effects of projection, the plane of the spiral lying obliquely to the line of sight."

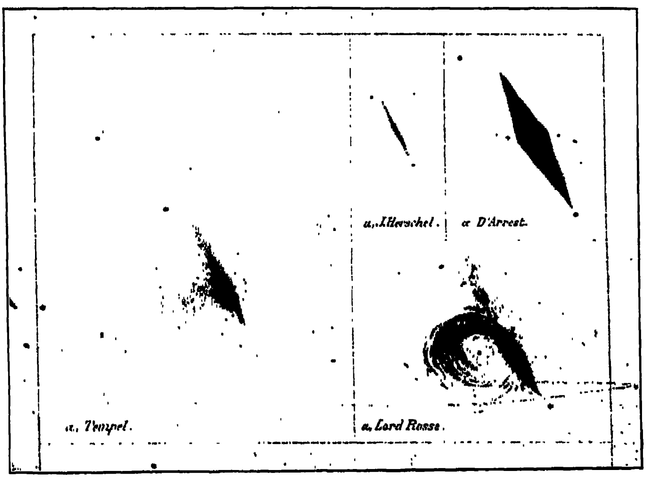
Lord Rosse's star occupies the centre of the space fenced round by the preceding branch (that to the left). "It would be of great interest," the Lick astronomer continued, "to know whether this singular position of the star is accidental, or whether the star and the nebula are physically connected, and if so, in what way the star was left in its present position during the process of contraction. On the first of these questions an investigation of the spectrum, which will be made in due time" (the time, alas! never came), "may throw light. Assuming for the present that the star is physically connected with the nebula, it seems to me possible that the proximity of this star may account for the unsymmetrical appearance of the spiral, which may be due to an actual difference in the dimensions of the two branches, or to their lying in differently inclined planes."

The first nebula in which a spiral conformation was recognised is still unsurpassed as a specimen of its class. We are enabled, by Mr. W. E. Wilson's kindness, to reproduce in Plate XXII. his fine picture of this stupendous object. The coils are left-handed; they follow, as they issue from the nucleus, the line of movement taken by the hands of a watch. Our view of them is straight and square; they can be little, if at all, foreshortened. Yet they do not wind symmetrically round their origin. Their flow is broken and distorted, like the current of a river by jutting rocks. The spiral is fundamentally double. Two main streams leave the nucleus at diametrically opposite points, and preserve their separate individuality until they melt away into the outer darkness. Their course seems to be prescribed essentially by the combination of an ejective with a rotatory velocity; disturbances, however, manifestly supervene. The branches divide and reunite; they are cloven and bossy; they swerve widely from the circular track. This is especially remarkable in the case of the longest and brightest arm, which stretches irregularly outward to join a secondary exterior nucleus. This circumstance alone suffices to prove that the diffusion of matter

1.



2.




1. Photograph of a Spiral Nebula in Pegasus. Taken by the late Professor Keeler.
2. Drawings of the same Nebula by Herschel, d'Arrest, Rosse, and Tempel.

in this formation has been outward. The perturbing mass was undeniably there before the luminous stream which it diverted began to flow; and its flow was quite plainly towards it from within. Other indications of centrifugal action are visible. Mr. Wilson's photograph shows "cometary tails curved like a plume away from the central nucleus," attached to some of the denser knots on the convolutions of the spiral;[1] and these effects of apparent repulsion are likewise clearly legible on Lick and Crowborough plates of the same object.

Indraughts or infalls from space are not here concerned, whereas, in Mr. T. C. Chamberlin's words,[2] "the effects of explosive projection, combined with concurrent rotation, must obviously give rise to a spiral form." Each such nebula (and there are tens of thousands of them) results, in his view, from the "approach without collision" of a roving star to a compact gaseous mass. Strained to the point of disruption by tidal influences, this embryo vortex would, at a given moment, project from both extremities of the ellipsoid into which it had become elongated, a stream of material curved into whorls through the continual slackening of its angular rate of rotation; and the double catastrophic outrush served to constitute a great system of shining spires, subsequently diversified by the supervening phenomena of minor outbreaks. This rationale has much to recommend it, and probably rests upon a substratum of truth; yet the events contemplated in it are on a small scale by comparison with the grandiose dimensions which we must ascribe to spiral nebulæ.

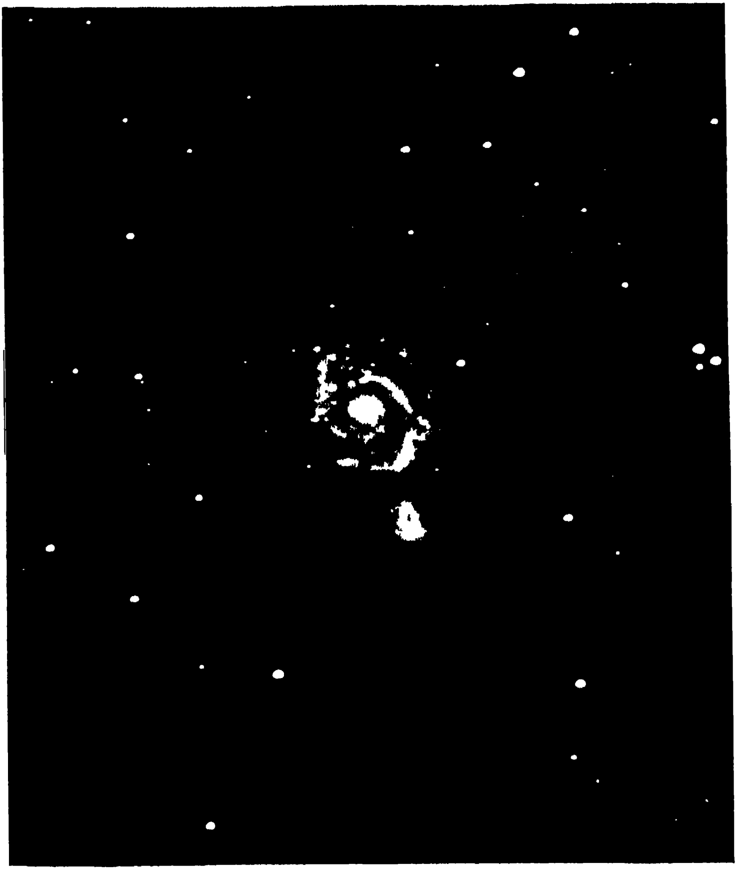
Lord Rosse described a nebula situated near the star 83 Ursæ Majoris (M 101 = N.G.C. 5457, 5458), as a large faintish spiral, with several arms and knots, at least 14′ across.[3] A four hours' exposure at Lick brought into view a surprising wealth of intricate details. The groundwork of the structure agrees closely with that of the great spiral in the Hunting Dogs. It is composed of two main effusions, sweeping round from left to right. But they spread, and split, and ramify, drawn hither and thither by multiple attractions, while preserving in their complex interlacings, the whirling impress of their origin.

[1] *Astronomical and Physical Researches at Daramona*, Appended Illustrations.
[2] *Astroph. Journ.* vol. xiv. p. 34. [3] *Trans. Royal Dublin Society*, vol. ii. p. 135.

"Three-branched spirals" still survive here and there in catalogues. Such were supposed to be the delicate objects, M 99 in Virgo (N.G.C. 4254), and M 83 in the head of the Centaur. But the triplicate form ascribed to them was most likely of optical creation. There is no satisfactory evidence that it exists in nature. So far as we can judge, the spiral type originated, by fundamental necessity, through a double outflow, in contrary directions, from the parent mass. A mode of genesis is intimated which recalls, though distantly, the diametrically opposed eruptions not uncommonly witnessed on the sun. It may be added that no genuine spiral appears to be a simple watch-spring coil. This, to be sure, is, to some extent, a matter of definition. It depends upon what we agree to call a spiral nebula. Yet the difference will most likely prove to be radical between stars with curving trains, like Maia in the Pleiades, and those cosmic "whirlpools," every trait of which testifies to the counterplay of multiple activities.

"Cometary nebulæ" are not very rare, and they present aspects of considerable variety. The nuclei are not always stellar, nor are the appendages attached to them in all cases inflected. A few have been photographed. Thus an object (N.G.C. 1999) 50′ south of ι Orionis was noticed by Lord Rosse as resembling "a comet coiled into a ring nebula,"[1] and appeared under the same form on a plate exposed by Dr. Common with his three-foot (now the Crossley) reflector in February 1883.[2] Its spectrum has not, that we are aware of, been examined. "Reaping-hook" shapes also occur. West of the Argo nebula, a falcated and forked tail, 10′ long, was observed by Sir John Herschel to issue from a granulated, perhaps a double nucleus[3] (N.G.C. 3199). The inner edge is sharp, but it fades gradually outward. Cometary, too, is N.G.C. 520. It has an indistinct nucleus and a bifid train.[4] A nebulous hyperbola with a star near the vertex (N.G.C. 2366) is met with in Camelopardalis;[5] and fan-shaped appendages to stellar condensations are a recognised variety of the species. A pair of these singular objects were photo-

[1] *Trans. Royal Dublin Society*, vol. ii. p. 50.
[2] *Observatory*, vol. xii. p. 84.
[3] *Cape Results*, pp. 20, 94.
[4] Rosse, *Trans. Royal Dublin Society*, vol. ii. p. 19.
[5] *Ibid.* p. 57.



Photograph of Whirlpool Nebula (M 51). Taken by Mr. W. E. Wilson, 6th March 1897.

graphed by Professor Barnard, 2nd February 1894,[1] in the immediate neighbourhood of the bright-line star $\gamma$ Cassiopeiæ. His sketch, showing their positions with regard to it, is copied in Plate XXIII. Fig. 1. These do not seem to be casual. The opening out of the two fans straight away from the star suggests an express plan of orientation. Each nebula is about 15′ in diameter. They are "excessively faint and dilute," and almost elude visual observation. In Professor Barnard's opinion, they would never have been detected otherwise than by chemical means.[2] Yet they photograph easily enough; and if this actinic quality denotes, as seems probable, a gaseous constitution, mention of them should, properly speaking, be postponed to a later chapter. Their spectral classification, however, is likely, for some time to come, to remain matter of conjecture. Dr. Roberts obtained, with ninety minutes' exposure on 25th October 1895, an excellent photograph of the twin fan nebulæ, in which traces of a luminous connection are apparent.[3]

"Rifted" nebulæ must be classed as a variety of the elliptical sort. They appear either as cloven discs—N.G.C. 5128 in Centaur is an example—or as parallel rays, such as a bifid streak in Leo (N.G.C. 3628). A probably analogous structure in Andromeda was photographed by Dr. Roberts in 1891.[4] It came out immensely elongated, and with just such a "chink in the middle" as had been seen by Sir John Herschel, whose opinion that the nebula was the foreshortened representative of a thin, flat ring of enormous dimensions thus received strong confirmation. Yet the added light-power of the Parsonstown mirror had extended Herschel's "chink" into a channel, running from end to end of the formation. Or rather the retinal impression afforded by it had been misinterpreted in this sense; for that it was a misinterpretation the camera incontrovertibly asserts. The error may serve as an illustration of Professor Keeler's remark that "the most obvious tendency of the draughtsman is to prolong a line or curve beyond the point at which it actually

[1] They seem to have been depicted two months earlier by Max Wolf. See *Astr. Nach.* Nos. 3214, 3217.

[2] *Astr. and Astrophysics*, vol. xiii. p. 183.

[3] *Celestial Photographs*, vol. ii. p. 159.

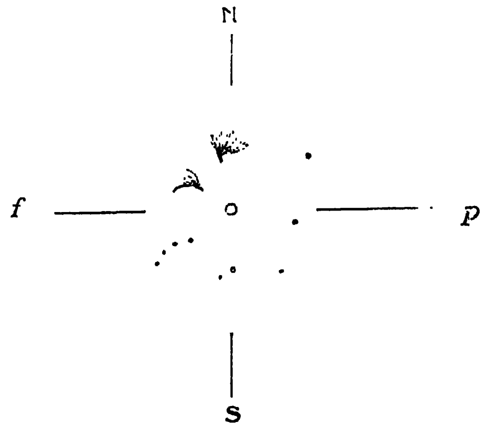
[4] *Ibid.* vol. i. p. 41.

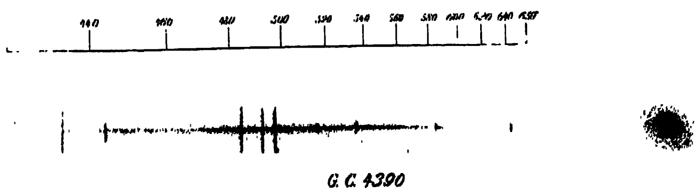
stops."[1] A suspicion even arises that other telescopic presentments of rays split throughout their length are similarly misleading, and that they are, in fact, like the glimmering oval in Andromeda, rings thrown into perspective. Otherwise why should the dark rifts always coincide in direction with the major axes of such formations? If these are really circular discs, they might as well run across as along them; but they never do. We must then choose between two inferences. Either the nebulæ are in fact, and not merely by optical projection, elliptical, in which case a longitudinal line of cleavage would be intelligible, or they are luminous rings viewed very obliquely. It must indeed be admitted that the strong development of nuclear condensations in some rifted nebulæ appears almost to exclude the latter alternative. Dr. Roberts's photographs, for instance, of N.G.C. 4565 in Coma Berenices, and of N.G.C. 4594 in Virgo,[2] exhibit an arrangement of parts insistently demanding a different explanation. What seems certain is that no single principle is valid all round. Modifications must be introduced to meet the exigencies of nature's endless variety.

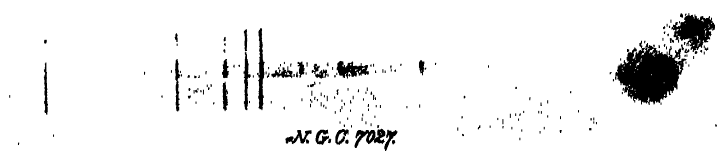
The great majority of white nebulæ might be called globular clusters in disguise. They present a round surface, condensed centrally by gradations testifying to their true spherical form. The only obvious distinction between them and "balls of stars" is that they are irresolvable by any telescopic powers that can be brought to bear upon them. And the suggestion lies close at hand that this quality depends wholly upon distance—that round nebulæ are neither more nor less than remote globular clusters. Yet it cannot be adopted without hesitation. The space-relations of the two classes of object are very different. Clusters frequent the Milky Way; white nebulæ avoid it. The discrepancy, it is true, may be capable of reconcilement, but by a somewhat elaborate artifice of speculation. Nor is there any immediate prospect of solving the difficulty by the aid of the spectroscope. We are unacquainted at present with any criterion for distinguishing continuous nebular light from that of compressed clusters. One may eventually be found, but its application must always be a matter of extreme delicacy.

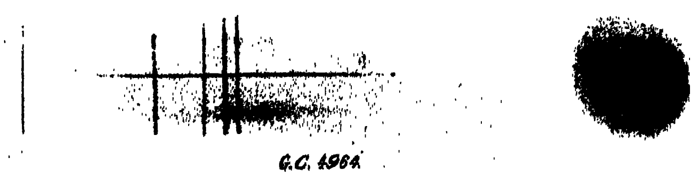
[1] *Astroph. Journ.* vol. xi. p. 4. [2] *Celestial Photographs*, vol. ii. p. 135.

PLATE XXIII.

1. 


2. 


3. 


4. 


1. Fan Nebulæ near γ Cassiopeiæ (Barnard).
2. Drawing of Struve's Planetary with Spectrum (Keeler).
3. Drawing of Webb's Planetary with Spectrum (Keeler).
4. Drawing of Annulated Planetary in Andromeda with Spectrum (Keeler).

Professor Max Wolf's explorations of the heavens show them to be strewn with an incredible number of small faint nebulæ.[1] Directly visible only by elusive glimpses, they come out individually distinct and measurable on sensitive plates; and the Heidelberg observer has already laid his plans for the construction of a photographic catalogue of nebulæ, likely to be at least twenty times more voluminous than the most exhaustive visual enumeration. In certain regions he indeed found that only two per cent of the dim objects delineated on his plates had been previously recorded. The newly discovered crowd vary greatly in shape. Some are round and compact; many more are round and diffuse; there are spirals among them, and spindles, and draped or arched formations. A surprising number are marked "planetary," and are hence, presumably, gaseous. The physical nature of the rest is inferable only when the definiteness of their shapes prescribe their arrangement in some established category.

Thus we are able to assert confidently that those disposed along coiling lines or projected into rays and ellipses, give continuous light; but if we attempt to go further, and obtain a clear conception as to how the light originated, embarrassments beset our path. Let us confront them fairly. The only white nebula of which the spectrum has been observed to any purpose is the great elliptical spiral in Andromeda. It almost certainly includes lines or bands of absorption; it is probably marked by traits of emission as well. Plausibility is thus lent to the opinion that the nebula is a genuine cluster of stars amalgamated by distance into a soft haze. The haze, however, shines very dimly; its lustre is almost evanescent comparatively to that of the sun. If, then, its component particles are true suns, they must be inordinately far apart. For the sake of giving some precision to our ideas on the subject, we will attempt to illustrate this numerically. If we assume the central parts of the nebula to possess $\frac{1}{200}$th the intrinsic lustre of the full moon, or (what comes to the same) $\frac{1}{124}$ millionth that of the sun, while consisting of scattered globes of solar brilliancy, it follows that this also is the proportion between the total bright area covered by their

[1] *Sitzungsberichte der kgl. bayer. Akad. der Wissenschaften*, Bd. xxxi. Heft ii. p. 111 (1901).

discs and the dark area of vacancy, the dimness of the nebula measuring the spread of the interspace. Hence the component stars, taking each to be half a million of miles in diameter, should be separated from its next neighbour by an interval of more than 5000 millions of miles, as seen projected upon a plane perpendicular to our line of vision. Their real distances, since they are presented to us slantwise, would of course be very much greater; but with them we are not just at present concerned. We must next try to form an estimate of how close together these sun-like bodies should appear to be in order to produce the observed effect of a smooth luminous surface. If the gaps amounted to one-tenth of a second, the nebula would certainly, with the powerful and perfect telescopes now in use, show symptoms of resolvability. Yet none appear. The fog does not even tend to condense into droplets, and the temporary star of 1885 stood out, to the last hour of its visibility, by contrasted light-quality from the soft surrounding glow. Allowing, then, that the linear intervals of 5000 millions of miles between the constituent bodies of the Andromeda nebula are represented by optical intervals of $\frac{1}{20}$th of a second, we arrive at a parallax for that vast structure of less than $\frac{1}{1000}''$. In other words, its rays spend about 3300 years in travelling to the earth. At this distance, the stars we have supposed aggregated in it would appear of fifteenth magnitude. Now they should in the fainter outlying parts of the nebula be more sparsely distributed than near the centre, and as they thinned off they would inevitably appear in their proper guise as fifteenth-magnitude stars. But the texture of the glimmering haze remains the same in every stage of attenuation.

It may then be taken as certain that, if this object be of stellar constitution, it is made up of stars smaller and closer together than we have supposed; unless we are prepared to lengthen still further, and very materially, a light-journey already protracted to the verge of the incredible. It is not, however, easy to conceive that bodies much less than half a million miles in diameter can be truly sun-like. An outpouring of light and heat in the profuse measure exemplified by the sun, implies storage-accommodation on a colossal scale; and the spectrum of the Andromeda nebula, so far as it

can be deciphered, seems to correspond to a high standard of temperature.

Undoubtedly the path "of least resistance" is to accept the stellar origin of nebular radiance. It is not entirely practicable, but every other is impassable. The solar corona presents no real analogy to white nebulæ, since it is kept incandescent by the potent agency of the sun, while their glow is self-sustaining. This it can only be—setting aside the vague possibility of electrical discharges—by the sacrifice of motion in some form. According to Sir Norman Lockyer's well-known hypothesis, the collisions of swarming meteorites supply the evolved energy; but there is little or no evidence that the cause acts, or would be adequate if it did act. We, at least, have no experience of its operation. The only meteoric collisions we know of are with the earth, which spreads a wide net for the capture of flying cosmic particles.

As an alternative suggestion it may be worth considering whether the shining of nebulæ might proceed from a very slow loss of circulatory speed through the resistance of a gaseous medium. A pulverulent constitution, resembling that of Saturn's rings, should then be attributed to them; they would consist of relatively small masses interfused with some highly subtle aerial remnant, the distinctive bright lines of which add complexity to the nebular spectrum. But the velocity of circulation in such structures should increase outward. Other things being equal, they should accordingly, if arrested motion were the source of their luminosity, gain brightness with increasing distance from the centre. The reverse is very markedly the case; but the attendant conditions are so intricate that the contradiction need not be fatal to the speculation. It cannot, however, be usefully discussed apart from a profound study of the dynamical condition of such a peculiar system as that just indicated; and this we must leave to more competent authorities.

# CHAPTER XXXII.

## DOUBLE NEBULÆ.

"DOUBLE nebulæ," Dr. See wrote in 1893,[1] "have been greatly neglected since the time of Sir John Herschel, but it is to be hoped that astronomers will again give adequate attention to these remarkable objects, which should be at once systematically studied and photographed. If accurate drawings or photographs of these objects were now made, it is not to be doubted that important changes could be observed fifty years hence."

His special interest in them originated from a research into the "evolution of stellar systems."[2] Sir John Herschel's drawings of coupled nebulæ illustrated most aptly his theory of the origin by "fission" of double stars, some appearing actually modelled upon Poincaré's "apioid"—the figure assumed by an ellipsoid when becoming unstable under the stress of increased axial rotation, and about to break up into unequal masses. Without entering into details regarding the process, it may be explained that disparity in the products of disruption indicates want of homogeneity in the parent body, so that the sooner the components separate, the greater the chance of their approximate equality. But the result of photographically investigating the pattern-objects was completely to alter the point of view from which they had to be regarded. "The actual nebulæ," Professor Keeler stated,[3] "have almost no resemblance to the figures. They are, in fact, spirals sometimes of very beautiful and complex structure, and in

[1] *Astr. and Astrophysics*, vol. xii. p. 300.
[2] Published as an "Inaugural Dissertation" at Berlin in 1892.
[3] *Astroph. Journ.* vol. xi. p. 347.

any one of the nebulæ the secondary nucleus of Herschel's figure is either a part of the spiral approaching the main nucleus in brightness, or it cannot be identified with any real part of the object." There had been premonitions to this piece of "destructive criticism." Many spirals are readily seen to be essentially duplex. Such is their exemplar in Canes Venatici, the second nucleus of which, separately catalogued by Sir John Herschel,[1] was brought into connection with the first only when the intervening whorl of nebulous matter disclosed itself at Parsonstown in April 1845. In many other cases, the brighter knots which tend to form on curving branches are seen isolated, for lack of light to bring the linking filaments into view, with the outcome of visually decomposing one formation into several. Thus telescopic improvements, which avail to analyse stars, have frequently a synthetic effect upon nebulæ. Even such adjacent objects as are presumably in mutual systemic relation, often show signs of being bound together by organic ties as well. Hence it is difficult to draw a line between single and double nebulæ. A pronounced "dumb-bell" form graduates insensibly into a pair of clearly individualised globes, barely united by a faint ligament. And their condition seems less alien to our ideas when we remember that the sun is nebulously connected with the earth by means of the zodiacal light.

Unification with increase of optical power was exemplified by Burnham's observation, at the Lick Observatory in 1891,[2] of a nebula as single, though binuclear, which Herschel had registered under two distinct headings (N.G.C. 7174, 7176). The condensations, which possibly offer to our view a double star in the making, are just 26″ apart, and belong to a nebular group in the Southern Fish. A more dubious object is situated in Aquarius (N.G.C. 7287). Detected by Müller at the M'Cormick Observatory, it was described as an "excessively faint, slightly nebulous double star." Burnham found the object to be indeed double at an interval of about 20″, yet not stellar, one component, at any rate, and perhaps both, appearing as small dim nebulæ. An authentic example of a double nebula was noted by Barnard in 1888, with the

[1] *Gen. Cat.* Nos. 3572, 3574; *Phil. Trans.* vol. cxxiii. p. 496.
[2] *Monthly Notices*, vol. lii. p. 458.

twelve-inch refractor of the Lick Observatory, in the neighbourhood of the wide double star 23 Orionis (Σ 696). The components are 36″ apart, faint and uncondensed. A tenth-magnitude star forms with them an equilateral triangle. Their measurement by Burnham in 1891 [1] supplies a datum of first-class importance for the future determination of change in the system which they beyond question constitute.

Littrow described in 1835 [2] a curious combination of three small nebulæ marking the angles of a triangle, the sides of which are formed by three nebulous bands, while a fine double star occupies the middle of the enclosure. The arrangement, met with near $\gamma$ Pegasi, would make a promising subject for a photographic experiment. Close telescopic scrutiny, on the other hand, might advantageously be brought to bear upon a nebulous pair in Gemini (N.G.C. 2371, 2372). The distance from centre to centre of the components is only 32″, and they were seen at Parsonstown to be connected by "tails and filaments," if not encircled by a filmy annulus.[3] An intermediate star, noted as "bright" 19th December 1848, was observed by Lassell in 1852,[4] and by d'Arrest in 1862, but has of late ceased to attract attention. Can it have lost light? D'Arrest seems to have had no difficulty in seeing it with an eleven-inch refractor, so the question might be readily answered. The preceding member of the pair was remarked by Dr. Dreyer in 1887 to be brighter and more condensed than its companion.[5] A similar nebular and stellar group was discovered by Dr. Common in 1880 [6] in the constellation Crater. He regarded the nebulæ as planetaries; in the absence, however, of information concerning their spectra this cannot be held certain. The existence of the linking star—a feature of peculiar interest—has not, we believe, been verified, but need not be doubted.

Fine telescopic seeing avails to resolve, no less than to unify nebulæ. Some split up, like close double stars, under high powers. With a magnification of 250 Professor

[1] *Monthly Notices*, vol. lii. p. 453.
[2] *Sterngruppen und Nebelmassen*, p. 33.
[3] *Phil. Trans.* vol. cxl. p. 512, plate xxxvii. fig. 6.
[4] *Memoirs Royal Astr. Society*, vol. xxiii. p. 62.
[5] *Monthly Notices*, vol. xlvii. p. 416.
[6] *Copernicus*, vol. i. p. 50.

Swift perceived a nebula (N.G.C. 6679), earlier discovered by himself, to be a well-separated pair, and he obtained a similar result for one of Sir William Herschel's. "It would," he adds, "be a great satisfaction to be fully assured that they are binaries."[1] We fear that the satisfaction is reserved for a future generation of astronomers. The Herschelian nebula in question was doubtless N.G.C. 3690 in Ursa Major, which had already in 1852 been divided with the Rosse reflector into two irregular masses at a distance of about 60″.[2] This is a coarse object compared with two delicate pairs discovered by Swift at Echo Mountain, California, in 1897. Each resembles a "double nebulous Uranus," the conjoined discs being 5″ or 6″ apart.[3] They are numbered 6 and 27 on his eleventh catalogue; yet, although one seems the replica of the other, they are not near neighbours in the sky. Mixed pairs, stellar and nebulous, are less scarce than one might expect. Swift's southern explorations yielded nearly a dozen specimens. Two are situated in Argo, near the small round nebula, N.G.C. 3267. Each proved resolvable, in the exquisite Californian air, into a star and nebula at a distance of 4″;[4] and the veteran observer's concluding list of discoveries included five analogous couples, the widest having a span of 8″. They should at once be micrometrically measured; for until this is done they cannot be said to have started on their career in scientific history.

Double elliptical nebulæ are picked up now and again. They are not easily distinguishable from rifted nebulæ. Probably the true criterion is the duplicity of the nucleus. Rays stretched parallel to the main formation, but exhibiting no trace of independent condensation, can only be regarded as outlying portions of it; where there are two nuclei, there are, *in esse* or *in posse*, two distinct bodies. As such two lens-shaped objects in Pegasus (N.G.C. 7814), photographed by Dr. Roberts,[5] should probably rank. The "dark lane" shown by the Rosse reflector was perceived in the negative to bisect the globe-like nucleus, and to widen out on either side of it; so

[1] *Popular Astronomy*, vol. i. p. 370.
[2] *Trans. Royal Dublin Society*, vol. ii. p. 97.
[3] *Astr. Nach.* No. 3517.
[4] *Monthly Notices*, vol. xlviii. p. 331.
[5] *Celestial Photographs*, vol. i. p. 131.

that each oval is complete in itself; neither looks like a fragment of the other. A true pair seems also to be constituted by the lenticular nebulæ (N.G.C. 3786, 3788) delineated by Spitaler at Vienna in 1893;[1] while the status of many more cannot be fixed until they have been photographed with a variety of instruments and exposures. Among those of uncertain nature should be reckoned a cloven ray in Leo (N.G.C. 3628), 15′ in extent,[2] and probably annular;[3] a similar object in Centaur (N.G.C. 5128), viewed with amazement by Sir John Herschel; a fissured ellipse in Leo Minor (N.G.C. 2964), thought to be "almost double" at Parsonstown; and a spindle in Draco (N.G.C. 5866), described by Professor Keeler as "divided lengthwise by a narrow, perfectly dark straight rift, on each side of which, near the north-preceding end, and involved in the nebulosity, is a minute star of about the sixteenth magnitude."[4] A bifid beam in Coma Berenices (N.G.C. 4565), 14′ long, and with a protruding nucleus, appears to be essentially single. Sir John Herschel noticed that the segments of rifted nebulæ are sharp on their confronted sides, diffuse outwardly.[5] They recall the gaping shell of a bivalve; and this peculiarity, if photographically persistent, might serve as a secondary mark of unity. The unity, as already pointed out, may be that of a ring viewed edgewise; or, in some cases, a formation primitively one may have been sundered by disintegration, as a rock-ledge is cut by a mountain torrent. This is, of course, said merely by way of illustration. We are unable to conceive how disintegrating forces in a nebula really act. Nor should the possibility be forgotten that the occurrence of black chasms may indicate, not the removal of matter, but an abolition of light. These apparently breached objects perhaps subsist, after all, in substantial entireness.

Double nebular ellipses do not invariably lie parallel to one another. The Andromeda nebula, for instance, is, in a manner, coupled with N.G.C. 205, the longer axis of which, as has been

[1] *Astr. Nach.* No. 3168.

[2] J. Herschel, *Phil. Trans.* vol. cxxiii. p. 403; Rosse, *Trans. Royal Dublin Soc.* vol. ii. p. 95; Spitaler, *Astr. Nach.* No. 3168.

[3] See a photograph by Roberts, *Celestial Photographs*, vol. ii. p. 135.

[4] *Lick Publications*, vol. iii. p. 204.

[5] *Cape Results*, p. 20.

said, makes an angle of 60° with that of its primary. A pair in Virgo (N.G.C. 4567, 4568) stand in yet more singular relations to each other. They coalesce at their following extremities, and diverge at an angle of about 45°.[1] They might be conceived of—were this mechanically possible—as revolving on a pivot. The combination is essentially reproduced by two spindle nebulæ near the hind foot of the Great Bear (N.G.C. 3786, 3788), which meet almost rectangularly. Dr. Spitaler's drawing of them is copied in Fig. 48. A third pair, similarly composed, was noted by Swift, 23rd September 1897, at the Lowe Observatory.[2] A bright nebula in Sculptor (N.G.C. 55) was then too seen to have a dim companion. Both are elongated; they meet obliquely and overlap. Possibly indeed they form together a single curved nebula; yet the indications are more in favour of a genuine coupled arrangement.

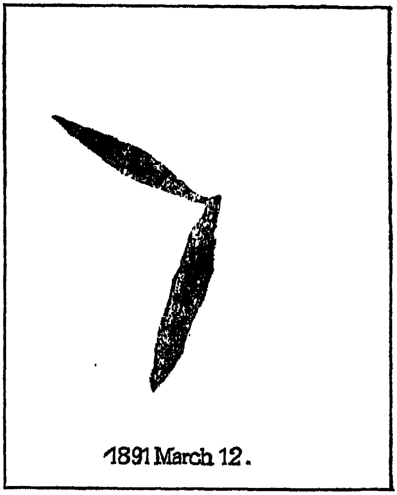



FIG. 48.—Drawing of Spindle Nebulæ (Spitaler).

Elliptical nebulæ are sometimes found less congruously associated with round, perhaps globular attendants. Thus an enormously long ray in Canes Venatici (N.G.C. 4631) is preceded by a tenth-magnitude star, and that again by a nebulous orb.[3] Of the ray, it was recorded at Parsonstown, 26th March 1848, that "masses of light appear through it in knots";[4] and the drawing made there exhibits helical lines corresponding presumably to an extensive system of foreshortened flat spires. The star does not appear to have been seen;

[1] *Trans. Royal Dublin Society*, vol. ii. p. 118.

[2] *Astr. Nach.* No. 3517.

J. Herschel, *Phil. Trans.* vol. cxxiii. p. 431.

[4] *Ibid.* vol. cxl. p. 512.

nevertheless it ought, unless greatly diminished during the score of years elapsed since Herschel's observation of it, to have been conspicuous with the six-foot speculum. A spindle-nebula in Eridanus (N.G.C. 1532) has also a round companion;[1] and two are attached to an ellipse depicted by Spitaler in 1893 (N.G.C. 2781, 2785). Triple combinations of round nebulæ are fairly common. The varieties of multiple stars are recapitulated in them. Single primaries have closely double satellites, or single satellites wait upon compound primaries. Three nebulæ, which, from their central brightening, may roughly be described as spherical, were detected by Barnard in 1886 lying close together in the field of his six-inch refractor.[2] Yet they are faint objects even with the Lick thirty-six-inch. The intervals between them were determined by Burnham in 1891 to be respectively 94″ and 78″. A century hence there will be hope of eliciting evidence of incipient revolution by the renewal of these measures. Another of Barnard's new nebulæ (N.G.C. 6302) was resolved by Swift into a triplet. It is plunged deep in the Milky Way in Scorpio, and has a gaseous spectrum.[3]

Compound nebulæ lead the way to groups and clusters of such objects. Swift counted twelve in a single field near Algol, and perceived at least twenty collected into a slightly larger space between $\kappa$ and $\gamma$ Herculis.[4] Barnard explored in 1890 a nest of eighteen small separate nebulæ in Ursa Major; and Max Wolf observed in March 1901 a real "Nebelhaufen" surrounding, though probably disconnected from the star 31 Comæ Berenices.[5] No less than 108 components, some elongated, some roundish and of various degrees of faintness, were found included in a circle 30′ in diameter; and a similar group, photographed in 96 minutes, has $\eta$ Virginis for its centre.[6] White nebulæ, in fact, tend very markedly to gather into flocks; whether as a consequence of their mode of origin, or through the compulsion of their mutual attraction, remains an open question. And since the

[1] J. Herschel, *Cape Results*, p. 22. [2] *Astr. Nach.* No. 2755.
[3] Pickering, *Harvard Circular*, No. 12.
[4] *Popular Astronomy*, vol. i. p. 370. [5] *Astr. Nach.* No. 3704.
[6] *Sitzungsberichte*, Munich, 23rd March 1901, p. 111.

masses of these bodies are likely to be very small, and their real distances very great, circulatory movements only of the most leisurely kind can be ascribed to them. We are unable as yet to forecast, even remotely, the establishment on a settled footing of the dynamics of nebular systems.

# CHAPTER XXXIII.

## NEBULOUS STARS.

"THERE is a vast difference," Professor Swift wrote in 1897, "between a nebulous star and a star in a nebula."[1] Vast indeed, since a star and nebula in reality billions of miles apart may be thrown by perspective into the same visual line, while a true nebulous star claims the ownership of its luminous appendage on the evidence of obviously adapted form. The nimbus is not more unmistakably fitted to the head of a saint in a picture than nebulous halos are, very often, to the stars they encircle. The relationship is patent. That the glow emanates from the star, and is no casual adjunct to it, the instinctive logic of the eye suffices at once to decide.

Sir William Herschel was the first to give express attention to "stars with burrs." They struck him as remarkable, not only in themselves, but for what they implied. They served as the basis of a memorable train of reasoning.[2] Their atmospheres, he argued, being plainly "not of a starry nature," must be composed of a "shining fluid," the same which is seen to be diffused through space in milky tracts, or curdled into fantastic shapes of chaotic irregularity. He was, in a word, led by them to the capital discovery of *nebulæ* as a distinct sidereal order. On 13th November 1790, he came across the "singular phenomenon" which determined his abandonment of the view that the universe is constituted exclusively of stars variously aggregated. This was "a star of about the eighth magnitude, with a faint luminous atmosphere of a circular form, and of about 3′ in diameter. The star is perfectly in the centre," he continued, "and the atmosphere is so diluted,

[1] *Astr. Nach.* No. 3517.

[2] *Phil. Trans.* vol. lxxxi. p. 71.

faint, and equal throughout that there can be no surmise of its consisting of stars, nor can there be a doubt of the connection between the atmosphere and the star." This exemplar object, situated in Taurus (N.G.C. 1514), he regarded as "decisive in every particular"; yet its nature is still to some extent dubious. It has even been classed of late as a planetary nebula, and certainly shares not a few characteristics of that family. The uncertainty of its status renders its study especially instructive.

A planetary nebula is definitely terminated; a nebulous star fades off into space. One shows a disc; the other is surrounded by an "atmosphere." Moreover, a star, or stellar nucleus, is subordinate in the one formation, while it dominates the other. These distinctions, however, cannot always be unhesitatingly drawn, since the relative strength of the stellar and nebular elements varies widely in different objects. Hence the doubt as to the category in which Herschel's typical specimen should be ranked. For the glow round it is uncommonly bright; d'Arrest found it to strike the eye with a four-and-a-half-inch refractor.[1] Nor is it equably diffused. The Parsonstown telescope showed it as spotted and patchy, and very curiously "ragged" at the edges;[2] and its aspect to Mr. Burnham in 1891 was essentially the same. A "broken and mottled" surface, about 126″ across, emerged in the field of the Lick thirty-six-inch.[3] He was inclined, though under reserve, to agree with Barnard in considering the object planetary. Its affinities might be settled by spectroscopic means; the attempt to do so could, at any rate, hardly fail to have an interesting result. So far, little has been ascertained about the spectra of true nebulous stars. Their halos, certainly in some cases, presumably in all, emit bright lines, and it might be expected that the same lines would show by absorption in the spectrum of the central star. The presumption has not, indeed, been fully verified; while the expectation founded on that presumption is disallowed by the facts scantily at our disposal. Stars with nebulous appendages are usually, if not invariably, dis-

[1] *Leipzig Abhandl.* Bd. iii. p. 314.
[2] *Trans. Royal Dublin Society*, vol. ii. p. 40; *Phil. Trans.* vol. cli. p. 714.
[3] *Lick Publications*, vol. ii. p. 161.

tinguished by "early Orion" spectra—a combination already noted as significant in connection with the course of sidereal growth; but they show no special lines that could be attributed to light-stoppage by the immense bulk of rarefied incandescent matter interposed between our eyes and their shining photospheres. This is one of the many perplexities involving the luminous relations of nebular stuff, which, setting "Kirchhoff's law" at defiance, exercises no absorption correlative to its emission.

One of the few nebulous stars bright enough for easy spectroscopic investigation is situated in Scutum Sobieski. Of 5·5 magnitude, it is enrolled in the Bonn Durchmusterung under the heading S.D. −10° 4713. On a plate exposed by Professor Barnard with the Willard lens, 29th June 1892,[1] a large diffused nebulosity was seen to encircle it. The appendage must be visually very faint to have escaped notice so long. Its proper spectrum may then be nearly evanescent. The star it belongs to is No. 8198 of the Draper Catalogue, where it is set down, although doubtfully, as of the second type (Spectrum E). Now this is a point of crucial importance to theories of stellar development. The pronounced nebulous condition of a star near the solar stage would have a bearing on such inquiries that could not be ignored. Should it be established, current ideas will need revision. The spectral character of Barnard's *nebulosa* in the Shield promises, indeed, to afford a test by which to try the validity of reasonings on sidereal evolution. The test ought, with the least possible delay, to be applied.[2]

A seventh-magnitude star in Eridanus was perceived by Swift in 1859 to be almost centrally placed in a shining corona.[3] It is perhaps identical with N.G.C. 5315. Its spectral classification should present no difficulty. A similar object, equally adapted for spectroscopic inquiry, was detected by the elder Herschel in Cepheus (N.G.C. 7023). The nebulosity is particularly strong north and south of the star. Irregularities of a more marked kind are apparent in other

[1] *Astr. Nach.* No. 3111.

[2] Since the above words were written it has been applied. Professor Frost examined, in September 1902, a spectrograph of S.D. −10° 4713 taken by Mr. Ellerman in 1899, and finds it to bear authentic marks of the helium type.

[3] *Sidereal Messenger*, vol. iv. p. 39.

instances. A tenth-magnitude star in Monoceros was found by Barnard visually nebulous in 1888, photographically in 1894.[1] A "small dark space," however, interrupts the encircling halo. A subsequent exposure with the same instrument disclosed as "closely nebulous" the 9·5 magnitude star, D.M. + 23° 1313.[2] And here again the illumination is unevenly distributed, the "fuzzy" border to the star-disc being denser south and east than elsewhere. This object lies almost midway between $\eta$ Geminorum and $\chi^2$ Orionis. One in most respects analogous (N.G.C. 2247), detected by Swift, 24th November 1883,[3] came out noticeably "blurred" on the same plate with Barnard's nebulous star in Monoceros. Two further specimens of the class were photographed by Barnard in Sagittarius. One—D.M. —19° 4948—is fainter than the ninth magnitude. It has a narrow fringe of light.[4] The second—D.M. — 19° 4953—is of 7·6 magnitude, and is encompassed by a far-spreading halo, 15′ in diameter,[5] conspicuous with the camera, although nearly invisible to the eye.

Nebulous stars are frequently compound—perhaps more frequently than stars clear of cosmic fog. Sir John Herschel recorded at the Cape a close pair (N.G.C. 5367) as involved in a bright glow two minutes of arc in extent; and a faint star with an aureola, discovered by Tempel in Cetus (N.G.C. 707), proved, when scrutinised by Burnham in 1891, to have a minute attendant at an interval of 10″.[6] A still more interesting detection concerned a nebulous triplet in Auriga (N.G.C. 1931). Discovered by Sir William, and described by Sir John Herschel as "one of the most curious objects in the heavens," it consists of three stars, the brightest of 9·5 magnitude, forming an equilateral triangle with a side of about 8″, placed precisely at the centre of a small circular nebula. Mr. Burnham had repeatedly inspected it with minor instruments,[7] but it needed all the power of the Lick refractor to bring into view a fifteenth-magnitude satellite at a distance of little more than 2″ from one of the stars of the triangle. As a test for "seeing" facilities, the pair is of

[1] *Astr. and Astrophysics*, vol. xiii. p. 177.
[2] *Ibid.* p. 181.
[3] *Astr. Nach.* No. 2683.
[4] *Ibid.* No. 3111.
[5] *Ibid.* No. 3101.
[6] *Monthly Notices*, vol. lii. p. 442.
[7] *Ibid.* p. 454.

unsurpassed delicacy. Again, a wide double star occupies the middle point of a pretty large faint nebula in Monoceros (N.G.C. 2182). The attendant may be only optically such; the circumstances are on this point indecisive. The chief star, however, was found by Mr. Burnham to be double in a perfectly unequivocal sense.[1] A companion of nearly its own magnitude (8·6) is separated from it by a spatial gap of less than half a second, and the two must assuredly revolve round their common centre of gravity. Here, indeed, we are confronted by a profoundly embarrassing question. The couple are evidently plunged in nebulous matter; their movements must then, according to received ideas, be impeded, with the result of an eventual collapse of the system. We can see no escape from the dilemma except by adopting the startling hypothesis that the nebulous fluid does not constitute a resisting medium. The difficulty greatly enhances the interest of spectroscopically determining the velocities of bodies nebulously connected.

A 6·5 magnitude star in Cepheus (D.M. + 57° 2309) appeared in a photograph taken by Barnard in 1893 "surrounded by a rather unsymmetrical dense nebulosity."[2] A "hazy glow" could be seen with the Lick thirty-six-inch, which, in Burnham's employment, had already revealed the star to be very unequally double at 4″.[3] A first-type spectrum is dubiously ascribed to it in the Draper Catalogue.

The nebulous triplet, ι Orionis, has been more completely observed than perhaps any of its congeners. It consists of a third and an eighth-magnitude star 11″ apart, with an eleventh-magnitude satellite at 49″, described by Admiral Smyth as "grape-red" in colour.[4] Sir John Herschel perceived the group to be "involved in a feeble nebula 3′ in diameter,"[5] and in the nebula (N.G.C. 1980) there was apparent with the Rosse reflector a central cavity containing the bright star-couple.[6] Possibly the effect was an illusion due to their effacing radiance; but this cannot be taken for granted, since

[1] *Publications of the Yerkes Observatory*, vol. i. p. 75.
[2] *Knowledge*, vol. xvii. p. 17; *Astr. Journ.* No. 447.
[3] *Publications of the Yerkes Observatory*, vol. i. p. 227.
[4] *Celestial Cycle*, p. 152 (ed. 1881).
[5] *Phil. Trans.* vol. cxxiii. p. 380.
[6] *Ibid.* vol. cxl. p. 514, fig. 16; *Trans. Royal Dublin Society*, vol. ii. p. 50.

"holes" in nebulæ are an attested phenomenon. And the early observations at Parsonstown approve themselves as singularly accurate through the confirmatory evidence of the best recent photographs. The spectrum of ι Orionis is of the helium type, and Dr. McClean identified in it three members of the Pickering series of hydrogen, besides many oxygen lines.[1] The surrounding glow emits the ordinary nebular rays, but they make no show, either directly or by reversal, in the dispersed stellar light. Yet before reaching outer space, that light has to traverse enormous volumes of incandescent or luminescent nebulium. The anomaly presented by the absence from the Fraunhofer spectrum of the solar coronal green line is here repeated in an emphasised form. A long nebulous streak, visible only on sensitive plates, links the hazy appendage of ι Orionis with the great formation in the Sword-handle.[2]

Far away in the northern part of the constellation, there is found in λ Orionis a combination very similar to that presented by the nebulous trio just considered. A yellowish and purple pair (Σ 738), of 3·7 and 5·6 magnitudes, at 4·2″, are immersed, with a comparatively remote twelfth-magnitude attendant at 29″, in a nebulous haze, photographed by Barnard in three hours, 17th September 1893.[3] The discovery was at once telescopically verified.

Five nebulous stars occur together in a narrow region of Sagittarius, and three of them are double. The two apparently single are Barnard's stars, already mentioned. The pairs are N.G.C. 6589 and N.G.C. 6590, both first noticed by Swift,[4] and N.G.C. 6595, delineated seventy years ago by Sir John Herschel. The character of an object photographed by Dr. Roberts[5] near the spiral nebula M 81 in Ursa Major, needs to be more satisfactorily determined. Known to Herschel and d'Arrest as a condensed nebula (N.G.C. 3077), it appeared on the sensitive plate with a sharp, stellar nucleus in lieu of the woolly disc visually perceptible.[6] The spectroscope may perhaps help towards its rightful classification. Nebulous stars

[1] *Phil. Trans.* vol. cxci. p. 129.
[2] W. H. Pickering, *Harvard Annals*, vol. xxxii. p. 66.
[3] *Knowledge*, vol. xvii. p. 17.
[4] *Astr. Nach.* No. 2707.
[5] *Monthly Notices*, vol. xlix. p. 363.
[6] Ingall, *ibid.* p. 420.

merge insensibly into stars with nebular appendages, such as $\omega$ Orionis and $\sigma$ Scorpii. The former has a dimly luminous, curved spur running out from it, besides a larger mass hanging like a cloud above it to the north; the latter is winged with nebulosity, two pointed projections issuing from it in divergent directions.[1] The whole of these appurtenances were detected photographically by Professor Barnard. Both stars afford spectra marked by helium absorption. The relations of stars and nebulæ are manifold. Misty trains and tails of all sorts and sizes have stellar foci; they emanate from stars, or condense into stars; but nebulous stars are, properly speaking, what Herschel called "stars with burrs"; they give the usual sharply defined diffraction-discs, although a dim halo spreads more or less symmetrically round each. The nebular element in such a combination is entirely subordinate to the stellar; while in stars with appendages the disparity gradually becomes reversed.

"Rejected" nebulous stars are still worth attention in view of the possibility that they may be subject to genuine change. The case of 55 Andromedæ is particularly instructive, if only as illustrating the propagation of error. This is a 5·6 magnitude star, qualified as *nebulosa* by Flamsteed and Piazzi, and regarded by Sir John Herschel as a typical specimen of a hazy star. It figures as No. 428 in his *General Catalogue of Nebulæ* (1863), but was omitted by Dreyer from the revised edition of that work. Sir William Huggins, nevertheless, observed it in 1864 to be "a fine nebulous star with a strong atmosphere;"[2] and since he used a very perfect refractor, his confirmation of what Herschel had seen with a reflector had an independent value which might seem to exclude the hypothesis of association in optical illusion. Yet neither Lord Rosse in 1848 nor d'Arrest in 1856 had perceived any trace of nebulosity, and Schjellerup, during some years previous to 1866, always found the star sharp.[3] So again it appeared to Mr. Burnham in 1879-80,[4] and so it seems likely to remain. We can, however, scarcely persuade ourselves that several eminent observers conspired to blunder;

[1] *Popular Astronomy*, Sept. 1897, pp. 229, 232.

[2] *Phil. Trans.* vol. cliv. p. 442.

[3] *Astr. Nach.* No. 1613.

[4] *Monthly Notices*, vol. xlii. p. 446.

and Schjellerup's theory that Piazzi merely repeated Flamsteed's note, which crept, he supposes, into the British Catalogue by a transference from the great Andromeda nebula, is rendered unacceptable by the circumstance that 55 Andromedæ follows the nebulous structure held to have been confused with it at an interval of considerably more than one hour of right ascension. Nor even if so extraordinary a mistake had been made, was Piazzi capable, one would think, of copying it unawares. His high astronomical reputation suffices in itself to clear him from the charge of such astounding carelessness. The spectrum of the star resembles that of the sun, a type never yet unequivocally associated with nebulous attachments. On the other hand, the normal quality of the light renders their optical creation more difficult of explanation. Thus the nebulous aspect of 55 Andromedæ must stand over as one of the unsolved problems of astronomical history.

A similar, but less convincing case is that of 8 Canum Venaticorum. On four separate occasions Sir John Herschel noticed this fourth-magnitude star to be surrounded by a "considerable atmosphere." Yet since no one before or after him has vouched for its presence, he was presumably deceived. The spectrum of 8 Canum is of the solar class.

Finally, a 7·5 magnitude star in Cetus, discovered as nebulous by Stephan at Marseilles in 1880[1] (N.G.C. 988), appeared to Burnham and Barnard in 1891 devoid of any such peculiarity.[2] A photograph taken with suitable exposure would serve decisively to test its present condition. The criterion might indeed fail with stars so bright as 55 Andromedæ and 8 Canum Venaticorum; for their imprinted discs would become, through chemical irradiation in the time needed to bring out faint glows, sufficiently distended for their obliteration.

In connection with nebulous stars two lines of inquiry open out. First, the spectroscopic. The scanty evidence at our disposal is to the effect that the stellar rays of such objects are of the "Orion" kind; that they show the quality believed to characterise suns in a primitive stage, while their aureolas shine like gaseous nebulæ. But these general-

[1] *Comptes Rendus*, t. xc. p. 837.
[2] *Monthly Notices*, vol. xlii. p. 446.

isations rest on a very narrow basis of fact, and probably admit of interesting and significant exceptions. Indeed, each nebulous star should be treated as a separate spectroscopic problem, destined to afford in the course of its solution insight into many obscure secrets. A second branch of research relates to the structural peculiarities of stellar halos. Their luminosity is seldom, perhaps never, equably distributed. Its irregularity sometimes goes so far as to produce the effect of dark vacuities, photographically attested to be no mere visual deceptions. What their true nature and origin may be, is a subject for inquiries likely to be long and arduous. It is scarcely credible that they are what they appear to be, obscure tunnels, striking, in the direction of the earth, right through the heart of immense spheres of shining tenuous matter. The alternative view is preferable that the so-called "atmospheres" of stars are really effluences—that they consist essentially of spiral coils wound closely enough to merge ordinarily into an approximately uniform surface, while leaving in certain circumstances conspicuous gaps between their luminous folds. If this be so, nebulous stars fall into line with cometary nebulæ, the trains of which take a more or less completely annular shape; but their nearest allies are unquestionably to be found in the planetary family; and this brings us to the subject of our next chapter.

# CHAPTER XXXIV.

## PLANETARY NEBULÆ.

Planetary nebulæ seem to be intermediate between nebulous stars and annular nebulæ. Indefinite aureolas are replaced in them, as if through the spreading outward of nebulous matter towards a limiting spherical surface, by compact discs, and with the further advance of this process of exterior condensation, the discs become rings. A stellar nucleus persists throughout these phases. They may not be strictly phases of development. To establish an actual sequence of growth, facts of various orders should be considered. As a simple matter of fact, however, objects are found which combine so closely the visual features of planetary nebulæ and nebulous stars on the one side, and of planetary and annular nebulæ on the other, that their classification in the above order is prescribed inevitably, if only for mental convenience.

As a preliminary to the physical study of these objects, we must try to attain a clear conception of their real forms in solid space. This is not easy when their structural complexities are taken into account; but, setting these for the moment aside, we can gather some indications regarding the general plan of their fabrication. As a rule, planetary nebulæ are markedly elliptical. They may then be concluded to be spheroidal in shape; and even those sensibly circular are probably spheroids viewed along their shorter axes. That their compression is due to axial rotation is a fair inference, verifiable, possibly, by spectroscopic measurements. These were indeed ineffectually tried by Professor Keeler, 3rd April 1891, on a bright planetary in Hydra (N.G.C. 3242);[1] but

[1] *Publ. Lick Observatory*, vol. iii. p. 203.

he doubted whether the conditions of the experiment permitted the detection of a difference in the velocities of the advancing and retreating limbs of the nebula of less than seven or eight miles a second, and the movement of such bodies is likely to be excessively slow. Otherwise they could scarcely be supposed capable of holding together; for they are obviously of tenuous composition, and gravity at their equators can act very feebly in equilibrating centrifugal impulse.[1] And here an untrodden field opens to enterprising inquirers. A theoretical investigation might, to begin with, be attempted of the figures which should belong to rotating globes of the kind on certain probable assumptions as to their nature and modes of movement; and the results might be tested by the application to a number of promising objects of Keeler's spectrographic method, in which the linear images of an equatorial slit serve, through the tilt imparted to them by the contrary motions of the opposite limbs, to measure, in miles per second, the speed of gyration. Small, lucid, strongly elliptical planetaries would be the most hopeful subjects for experiment; nor would a negative upshot be without value. The Hydra nebula, for instance, which is nearly as much flattened as the globe of Saturn, is equal in light to a seventh-magnitude star; it is about 20″ across, and somewhat diffuse at the edges.[2] With it may be compared a condensed planetary in Ophiuchus (N.G.C. 6572), sometimes called Struve No. 6 ($\Sigma$ 6). Its light, which is comparatively intense, emanates from a small disc 8″ in diameter (exclusive of a hazy margin), with an ellipticity of about $\frac{1}{200}$. Professor Keeler's drawing of the object with the visible part of its spectrum is copied in Plate XXIII. Fig. 2. The nucleus is not stellar, although it gives strongly continuous light. The lines in its spectrum were found by Keeler to be displaced upward by an amount corresponding to a motion towards the earth of 6·3 miles a second;[3] but this motion should be considered to belong to the sun, not to the nebula. Judging by its appearance, axial acceleration may have advanced farther in it than in most members of the class, and might record itself in an equatorial spectrograph. The

[1] Cf. J. H. Jeans, "On the Stability of a Spherical Nebula," *Phil. Trans.* vol. cxcix. A, p. 1.

[2] Ginzel, *Astr. Nach.* No. 2829.

[3] *Lick Publications*, vol. iii. p. 209.

trial, at any rate, should be made. Anticipation of failure need not be allowed to paralyse effort. In science the rush of a forlorn hope often carries a fortress that has obstinately held out against a siege in regular form.

The uniformity of aspect at first supposed to characterise planetary nebulæ disappears before the searching scrutiny of the powerful telescopes now in use. Their surfaces prove to be full of suggestive detail. They are broken up by irregular condensations, or furrowed by the operation of antagonistic forces; they betray, here possibly the action of repulsive, there of attractive influences, and bear inscriptions of no less profound historical import than the contortions and faultings of terrestrial strata. They are quite commonly multiplex formations. One glimmering disc is superposed upon another, intimating the analogy of the successive filmy envelopes flung round the heads of active comets. With the twenty-seven-inch Vienna refractor Vogel succeeded, in 1883, in resolving the above-mentioned planetary in Ophiuchus (N.G.C. 6572) into three distinct layers,[1] doubtless representing concentric ellipsoids of unequal antiquity. A triple outpouring of matter at age-long intervals seems recorded. And the case is typical, although the nebulous shells are not often so clearly defined. This, however, is, on the one hand, a matter of telescopic seeing; on the other, perhaps of evolutionary progress. By way of illustration, let us take as the first term of a sequence an average nebulous star, such as that detected by Auwers in Auriga (N.G.C. 2175); next in order we might place an object near 16 Cygni (N.G.C. 6826), in which the "glow" has become compacted into a large, round, seemingly uniform disc.[2] Sir William Herschel described it as "a beautiful phenomenon, of a middle species between the planetary nebulæ and the nebulous stars."[3] The following term of the series may be found in a planetary not far from γ Eridani (N.G.C. 1535), consisting of an eleventh-magnitude star, embossed upon two concentric nebulous shields; or rather, presumably, enclosed within a pair of nebulous globes. If we suppose these to have been produced by successive outflows, checked at a limiting

[1] *System of the Stars*, p. 256, Fig. 35.
[2] *Publ. Lick Observatory*, vol. iii. p. 212.
[3] *Phil. Trans.* vol. xcii. p. 522.

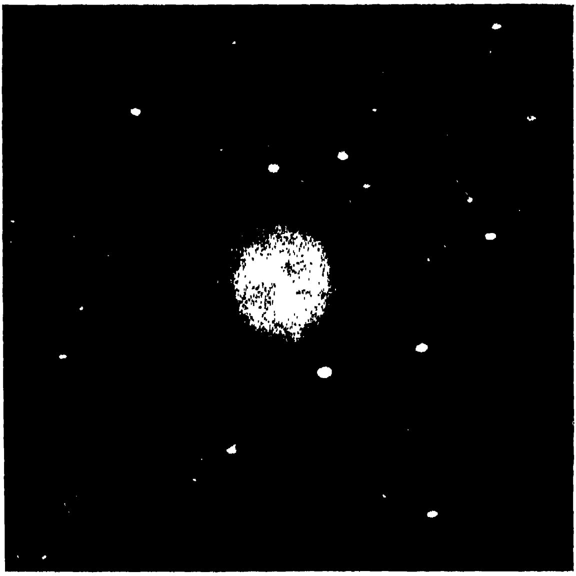
surface, we could easily see that the occurrence of a third access of ejective energy would complete the model of the triple specimen in Ophiuchus. It may be added that the difficulty appears almost insuperable of explaining the growth of multifold planetaries on the hypothesis of simple contraction. A repulsive agency in a manner asserts its past activity.

Let us now imagine one of these spherical envelopes to be hollow. The effect to the eye would be that of a luminous ring. And, in fact, an appreciable proportion of planetary nebulæ show an interior circlet of dim radiance, which can hardly be otherwise interpreted than as the projection on a plane of a vast nebulous bubble. This mode of construction is fully carried out in "annular nebulæ"; it is partially realised in not a few specimens in which a ring within a disc is perceptible or conspicuous. All will be considered together in the next chapter; in this we are concerned only with examples devoid of—so to speak—symptoms of inflation.

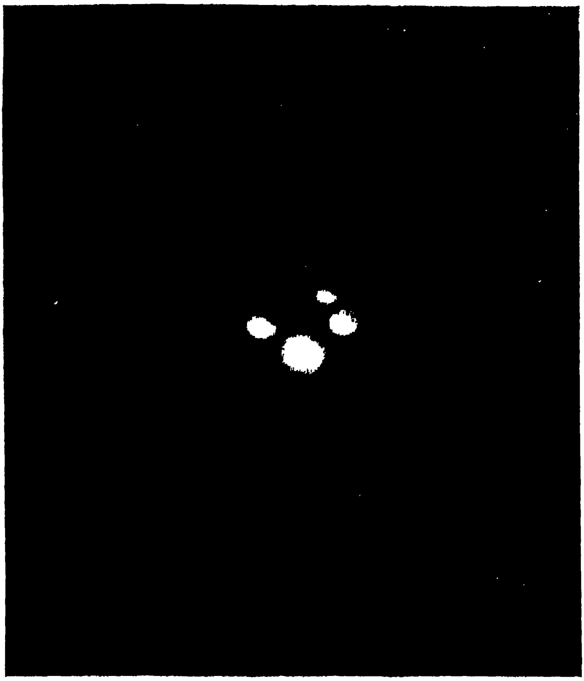
The largest planetary in the heavens lies south-east of the second Pointer, $\beta$ Ursæ Majoris. Discovered by Méchain in 1781, it was numbered 97 on Messier's list (N.G.C. 3587), and has been extensively and carefully observed. Its dimensions were given by Lord Rosse in 1874 as 163″ by 147″;[1] but the major axis measures 203″ on a photograph taken by Dr. Roberts, with an exposure of four hours, 20th April 1895,[2] and reproduced, by his kind permission, in Plate XXIV. Fig. 1. The observational history of the object is extremely curious. Sir John Herschel saw "a large, uniform, nebulous disc, quite round, very bright, not sharply defined, but yet very suddenly fading away to darkness."[3] On 2nd March 1848, however, Lord Rosse perceived a doubly perforated surface, with a star in each cavity,[4] and his observations were confirmed by Dr. Robinson. The drawing representative of them is a record of permanent interest. The resemblance to an owl's face, given to it by the symmetrically placed *oculi*, is unmistakable; and the great planetary in Ursa Major became known, from the middle of the last century,

[1] *Trans. Royal Dublin Society*, vol. ii. p. 93.
[2] *Celestial Photographs*, vol. ii. p. 127.
[3] *Phil. Trans.* vol. cxxiii. p. 402.
[4] *Ibid.* vol. cxl. plate xxxvii. fig. 11, p. 513.

1.



2.



1. Photograph of the Owl Nebula (Roberts).
2. Photograph of the Orion Trapezium (W. H. Pickering).

as the "Owl Nebula." The name has survived the similarity. On 9th March 1850 the two stars were noted at Parsonstown shining as usual in their respective excavations; five weeks later the fainter one had vanished;[1] nor could it ever again be found, though looked for about forty times during the ensuing quarter of a century. To Professor Keeler in 1891[2] the nebula wore indeed an entirely different aspect from that previously attributed to it. "There is but one nucleus," he stated, "which is by estimation almost exactly central, at a place which in Lord Rosse's drawing is occupied by a bridge of light between two dark openings. There is also but one central dark space." Nevertheless, two appear in the Crowborough picture, like lagoons separated by an isthmus, and on the isthmus there is planted, as it were, a lighthouse, diffusing a brilliant illumination. Thus the interior vacancies remain in *statu quo*, while the stars that formerly occupied them have both faded out of sight, leaving the prodominance to a third, not identical with either. The change, in short—admitting that there has been change—relates, not to the structure of the nebula itself, but to the relative brightness of three connected stars. The question whether those at present extinct will ever become revivified, can be answered only by prolonged experience. Dr. Roberts thought that his photograph indicated for the nebula a combined ring and disc formation;[3] but this is not manifest. The picture affords no verification of the marginal inequalities recorded at Parsonstown; yet there is reason to believe that they were not illusory. The torn and jagged contour, which Professor Alexander expounded as the effect of "disruption and dispersion outward,"[4] may come into view in representations on a larger scale, taken with special precautions for the definition of minute details.

The suspected alteration of the Owl planetary accentuates the need for keeping watch over nuclear stars, more especially since they present unexplained peculiarities. Their light is of purely stellar quality, but of remarkable actinic power. They

[1] *Phil. Trans.* vol. cli. p. 721.
[2] *Publ. Lick Observatory*, vol. iii. p. 203.
[3] *Monthly Notices*, vol. lvi. p. 379.
[4] *Astr. Journ.* vol. ii. p. 141.

are very much brighter chemically than visually. Further, they often give nebulous images on the sensitive plate, while appearing sharp with the telescope. In some rare cases (as in N.G.C. 6781), they are eccentrically situated. Burnham is probably justified in regarding the possession of a central star as an essential feature of planetary nebulæ,[1] although it is occasionally undiscernible with the telescope. N.G.C. 6563 in Sagittarius, and N.G.C. 7354 in Cepheus, are examples of nebulous discs unrelieved to the eye by the sparkle of any stellar points; and a beautiful little planetary in Perseus, discovered by Barnard 11th December 1890,[2] is of similar aspect. The missing nuclei, however, of all such objects would, it is tolerably certain, become manifest in long-exposed photographs, which should accordingly be taken for the purpose of deciding a point of fundamental importance in the economy of planetary nebulæ.

Perhaps the most noted member of the class, from the numerous experiments of which it has been made the subject, is located in Draco (N.G.C. 6543), quite close to the pole of the ecliptic. To ordinary observation it presents a greenish-blue surface, 22″ by 18″, centred on a vividly white star of the tenth magnitude; but Professors Holden and Schaeberle recognised, with the Lick refractor, its "helical" conformation.[3] Two brighter intersecting hoops, perceived at a glance to diversify the disc, fell into position on closer scrutiny as the thread of a screw, uniting their curves into one continuous tri-dimensional spiral. The discernment of this novel form—believed to be typical—was a suggestive contribution towards what might be termed the solid geometry of nebulæ. Speculations as to its mode of origin would, however, be premature until, by the unerring testimony of the camera, it has been definitively proved to subsist.

The Draco planetary was observed on the meridian by Lalande 26th July 1790, and there are no good grounds for holding it to have since shifted appreciably from the place then assigned to it. Burnham, it is true, has found a progressive diminution of the distance between the central star of the nebula and one external to it, amounting to 0·033″

[1] *Publ. Lick Observatory*, vol. ii. p. 159.
[2] *Astr. Nach.* No. 3017; Burnham, *Monthly Notices*, vol. lii. pp. 33, 449.
[3] *Ibid.* vol. xlviii. p. 388.

annually;[1] but the movement, if real, may confidently be ascribed to the disconnected star. The nebula is indeed very far from being stationary in space. Professor Keeler determined for it spectroscopically in 1891 a velocity of approach towards the solar system of forty miles a second;[2] and its apparent fixity on the sphere is doubtless only an effect of extreme remoteness. Some attempts to determine its annual parallax[3] have resulted only in showing it to be small "below compute." From the prismatic examination of this object, 1st August 1864, Sir William Huggins learned the existence of gaseous nebulæ.

A nebula in Cygnus (N.G.C. 6826) was described by Mr. Burnham as "almost an exact duplicate" of the planetary in Draco. It is nearly circular, the longer diameter measuring nearly 27″, the shorter 24″. The nucleus is very bright (8·8 magnitude), and gives a strong continuous spectrum. The light from the disc, too, includes an unusually large *white* ingredient.[4] The radial motion of this nebula is very small; it approaches the sun by 3·3 miles a second. But the sun is travelling on its own account towards its place at a much higher rate of speed, so that the apparent sluggishness of the nebula indicates that it is really moving away from us, its measured pace representing only the velocity with which our system gains upon it.

The spectra of planetary nebulæ are fundamentally alike; they differ only in details. About forty bright lines have been determined in them, visually and photographically, and they are invariably fine and sharp, as if emitted by materials of great tenuity. They seem hazy only just where they cross certain diffuse nuclei; and this feature seems to imply a gradual condensation of the nebulous stuff towards the central mass, which, in such cases, cannot properly be called a star. The essential characteristic, however, of nebular light is the presence in it of the ray, or rays, of "nebulium." This is the one sure criterion by which gaseous nebulæ can be distinguished from stars.[5] The chief nebulium

[1] *Monthly Notices*, vol. lii. p. 40; *Publ. Lick Observatory*, vol. ii. p. 165.

[2] *Ibid.* vol. iii. p. 217.

[3] *Astr. Nach.* No. 1885.

[4] *Publ. Lick Observatory*, vol. iii. pp. 212, 217 (Keeler).

[5] This assertion must be qualified if Miss Cannon's observation of the line $\lambda$ 5007 in certain members of the Wolf-Rayet family be substantiated. *Harvard Annals*, vol. xxviii. p. 141.

line has a wave-length of λ 5007, and is of a clear green colour. With it is constantly associated a ray about one-third as bright at λ 4959, and the invariability of their relation lends strong probability to the opinion that both emanate from the same substance.[1] A strong ultra-violet line at λ 3727, photographed for the first time by Sir William and Lady Huggins in 1882, perhaps claims an identical origin. This, however, remains doubtful in the absence of decisive evidence that it is an unfailing constituent of the nebular spectrum. The green gas designated "nebulium" is unknown, so far, terrestrially; nor has it been observed to shine in any of the heavenly bodies except nebulæ. There is reason to believe it denser, or at any rate less diffusive than hydrogen. An object catalogued in the Southern Durchmusterung as a ninth-magnitude star under the title S.D.M. $-12°$ 1172, was found by Mrs. Fleming in 1891 to give the spectrum of a planetary nebula. But hydrogen glows in it with unusual intensity. The relative brightness of the three green lines is estimated by Campbell[2] to be ordinarily 10:3:1, F (H$\beta$) being the faintest and most refrangible. But the proportion in the planetary near Rigel is 10:3:7. In other words, hydrogen is of seven times its normal lustre comparatively to nebulium. Further, the three lines, when viewed through an open slit, form discs of severally 11″, 9″, and 14″ diameter. Here then, apparently, a hydrogen-envelope constitutes an outer shell to the nebulium-sphere; and a gas that rises higher than another is presumably specifically lighter, although, in view of the enormous altitudes attained by calcium vapour near the sun, the inference must be regarded as subject to qualification. Certainty on the point, and on many others connected with the physics and chemistry of nebulæ, may be said to be unattainable until nebulium is captured in the laboratory. And the prospect of this achievement, although not hopeless, is remote.

The following table gives the wave-lengths and origins, when they are known or can be conjectured, of forty bright lines in the spectra of planetary nebulæ. A few are common to all, notably the trio in the green, with about half a dozen of

[1] Wilsing and Scheiner, *Astr. Nach.* No. 3305.

[2] Campbell, *Astr. and Astrophysics*, vol. xiii. p. 494.

the blue and ultra-blue hydrogen lines, while others are more individual in their occurrence; but, on the whole, bodies of this class seem to be of remarkably uniform constitution.

LINES OBSERVED IN THE SPECTRA OF PLANETARY NEBULÆ.

| Wave-Length. | Origin. |
|---|---|
| 6563 | Hydrogen ($H\alpha$). |
| 5876 | Helium ($D_3$). |
| 5751 | Oxygen ? |
| 5680 | Unknown. |
| 5540 | Unknown. |
| 5412 | Hydrogen; Pickering series ? |
| 5313 | Unknown. |
| 5183 | Unknown. |
| 5007 | Nebulium. |
| 4959 | Nebulium ? |
| 4861 | Hydrogen ($H\beta$). |
| 4790 | Unknown. |
| 4743 | Unknown. |
| 4715 | Unknown. |
| 4688 | Hydrogen; Rydberg series ? |
| 4662 | Unknown. |
| 4643 | Nitrogen ? |
| 4610 | Nitrogen ? |
| 4597 | Nitrogen ? |
| 4574 | Silicon ? |
| 4472 | Helium. |
| 4390 | Helium. |
| 4363[1] | Unknown. |
| 4341 | Hydrogen ($H\gamma$). |
| 4265 | Unknown. |
| 4145 | Unknown. |
| 4122 | Helium ? |
| 4102 | Hydrogen ($H\delta$). |
| 4067 | Unknown. |
| 4026 | Helium. |
| 3970 | Hydrogen ($H\epsilon$). |
| 3968[1] | Unknown. |
| 3889 | Hydrogen ($H\zeta$). |
| 3869[1] | Unknown. |
| 3836 | Hydrogen ($H\eta$). |
| 3795 | Hydrogen ($H\theta$) |
| 3768 | Hydrogen ($H\iota$). |
| 3727 | Unknown. |
| 3460 | Unknown. |
| 3390 | Unknown. |

[1] A formula connecting these three lines into a series has been published by Mr. E. F. J. Love (*Monthly Notices* vol. lxii. p. 524), but their conformity to it may be purely accidental.

Several of the Wolf-Rayet lines, it will be observed, are comprised in this list, notably those at λ 541, λ 469, and λ 464. And the absence of recognisable metallic rays strengthens the analogy with stars of that peculiar description. As a rule, the hydrogen spectrum in planetaries begins with the green line. The red line has been distinguished in only a few specimens, which appear more condensed than the rest. Yet it would be rash to assume that this is really the case.[1] The relative intensity of the hydrogen lines in stars and nebulæ is an intricate subject, the ramifications of which have yet to be tracked out. The coincident appearance of $D_3$ with C is worth notice as a hint that the conditions favourable to the development of the slower light-vibrations are the same for helium as for hydrogen. They are markedly present in Struve's planetary in Ophiuchus (N.G.C. 6572 = G.C. 4390), which gives a complex spectrum of at least thirty lines,[2] accompanied by faint continuous radiance. Three classes of fact regarding it are recorded in Professor Keeler's sketch of the portion of it accessible to eye-observations (see Plate XXIII. Fig. 2): first, the positions of the component rays in the scale of wave-lengths; next, their relative lustre; thirdly, the extent of the nebula from which they are derived. And it is of interest to perceive that only those associated with nebulium, together with the green and blue lines of hydrogen ($H\beta$ and $H\gamma$), seem to reach the limits of the disc, while the others are radiated only by its central parts. Still we have to remember that the length of the lines must depend to some extent upon their intensity; and that they may be short only because the sections of them given out by dim regions of the nebula are of evanescent faintness. Professor Keeler suspected the presence of dark bands interrupting its continuous light between $D_3$ and λ 5007,[3] and they will, if verified, supply the only extant proof of absorption in gaseous nebulæ. The nucleus of Σ 6 apparently reinforces the emissions from the disc; but it is plainly not a genuine star.

[1] Ferry's experiments at Upsala in 1898 went to show that C gains in relative strength with *diminishing* pressure (*Physical Review*, vol. vii. p. 6).

[2] Campbell, *Astr. and Astrophysics*, vol. xiii. p. 496.

[3] *Publ. Lick Observatory*, vol. iii. p. 209.

Further spectrographic investigation of the object is most desirable.

In the Draco planetary (N.G.C. 6543), on the contrary, the stellar and nebular elements of the spectrum are perfectly distinct. Some of the bright lines can indeed be seen only when the central star is outside the slit, and are therefore due, in Professor Campbell's words, "to the nebula proper, as indeed are all the lines observed, and there is no evidence to show that they exist at all in the central star."[1] A few of those registered in Struve's planetary are missing here, particularly the hydrogen line (Pickering series) at λ 541; but C, $D_3$, and both the Wolf-Rayet blue radiations are perceptible, while the leading ultra-violet line at λ 3727 appeared conspicuously in Von Gothard's photographs.[2] The relative strength of the green lines in this nebula, as determined by Campbell, is 10 : 3 : 2. It is of a verd-antique hue, and, indeed, the nearly total suppression of red rays in their light gives to all planetaries a blue or greenish tinge.

One of the Durchmusterung stars in Cygnus (D.M. +41° 4004) was noticed by the late Prebendary Webb, 14th November 1879, to have a hazy disc, some 10″ in diameter.[3] Stephan, at Marseilles, independently detected its nebular character, and Winnecke compared it to a small comet with a tenth-magnitude nucleus at its preceding end. Moreover, the nucleus is double. Professor Keeler described the object (N.G.C. 7027) as follows:[4]—"This is the brightest nebula that I have examined, and its spectrum is exceedingly interesting. The nebula is irregular in outline, and contains two central condensations, one of which has an oval and fairly well-defined outline. The other is much fainter and more diffuse." His drawing of it, made at the great telescope, is copied in Plate XXIII. Fig. 3, together with a representation of its spectrum. The nuclei are obviously non-stellar. The continuous spectrum of even the more conspicuous member of the pair is not incomparably brighter than that derived from the disc, and it claims all the emission rays as properly,

[1] *Astr. and Astrophysics*, vol. xiii. p. 495.
[2] *Ibid.* vol. xii. pp. 52, 55.
[3] *Astr. Nach.* Nos. 2292, 2293, 2309.
[4] *Publ. Lick Observatory*, vol. iii. p. 214.

though not exclusively belonging to it. Professor Keeler accordingly regarded it as "in a much less condensed state than the nuclei of $\Sigma$ 6 and many other nebulæ of its kind," its exceptional brilliancy notwithstanding. The spectrum of Webb's planetary is remarkable for the intensity of some usually quite subordinate lines, especially of the Rydberg hydrogen ray ($\lambda$ 4688), and of the unknown lines at $\lambda$ 4743 and $\lambda$ 4363. Campbell could just identify the red glint of C,[1] which by its faintness evaded Keeler's survey; $D_3$ was made out by both observers, and an unidentified line at $\lambda$ 3869 was photographed by Von Gothard in 1892, although his plates were blank at the place where the significant $\lambda$ 3727 was expected to appear.[2]

A companion to Webb's nebula, both in physical aspect and by vicinity in the sky (N.G.C. 7026), was discovered spectroscopically by Dr. Copeland in 1880.[3] It had, however, been observed telescopically by Mr. Burnham seven years earlier.[4] It is small, bright, duplex, a pair of diffuse nuclei 6″ apart sustaining a filmy structure which, viewed with the Lick refractor, suggested a comparison to two sheaves of corn laid side by side.[5] Burnham refuses to admit the planetary nature of either of the objects in Cygnus,[6] yet their spectra scarcely allow them to be relegated to a different class. The "Rydberg line" is equally prominent, relatively to their brightness, in both objects. From the cosmogonic point of view they are of high illustrative importance. We seem to have before our eyes double stars in slow course of formation, and preparing to break loose by the development of systemic revolutions from the trammels of a joint rotation.

Bi-nuclear planetaries are not uncommon. One such (N.G.C. 3195) was observed by Sir John Herschel in the south polar constellation of the Chameleon, and is depicted in his volume of *Cape Results*. The nuclei are fairly well matched in lustre, and will perhaps grow into a double star like $\gamma$ Virginis. Their spectrum is still unrecorded; but it

1 *Astr. and Astrophysics*, vol. xiii. p. 498.
2 *Ibid.* vol. xii. p. 55.
3 *Astr. Nach.* No. 2353; *Copernicus*, vol. i. p. 2.
4 *Monthly Notices*, vol. xxxiv. p. 71.
5 Keeler, *Publ. Lick Observatory*, vol. iii. p. 214.
6 *Monthly Notices*, vol. lii. pp. 45, 46.

will be of considerable interest to determine whether it exhibits the peculiarities visible in those of the double planetaries in Cygnus. Two bright patches near opposite margins of the circumference give the nebula in Chameleon somewhat the air of a reduced copy of the celebrated "Dumbbell" in Vulpecula.

Of a planetary in the Poop of Argo, originally discovered by the elder Herschel, Lassell wrote at Malta about 1851:[1]—"No description can do justice to this singular object," which is "not beautiful, for it has no symmetry, but wonderful." His drawing shows the disc, which had appeared to d'Arrest perfectly round, as pear-shaped, with multiple condensations. So that a quadruple or quintuple star in embryo may here be offered for our contemplation.

"Stellar" nebulæ have been mostly discovered by Pickering's method of sweeping with a direct-vision spectroscope. There is probably no radical difference between them and planetaries, for their comparative minuteness may be a simple effect of distance. Or they may be constructed on a reduced scale. We should naturally expect to meet in nebulæ a variety of dimensions not inferior to that existing among stars. Moreover, they are all alike gaseous, and give—so far as is yet known—perfectly similar spectra. Nevertheless, Mr. Burnham writes of the stellar kind as "very small, bright, round nebulæ, which in a small instrument would resemble stars slightly out of focus, but do not appear to come within the planetary class."[2] An admirable specimen was detected spectroscopically by Pickering 16th July 1882. Previously registered as a 9·4 magnitude star, it took rank, on the strength of its bright lines, as a stellar nebula (N.G.C. 6790). The Lick thirty-six-inch showed it to be round and lucent, with a minute nuclear point.[3] A miniature of Struve's planetary in Ophiuchus seemed to float in the field of the telescope. Without a slit, the spectrum, examined by Keeler, resembled three tiny greenish *stars*, that formed on $H\beta$ being much the faintest. This stellar nebula accordingly is analogous to Webb's planetary in the feeble

[1] *Memoirs Royal Astr. Society*, vol. xxiii. p. 61.
[2] *Monthly Notices*, vol. lii. p. 31.
[3] *Publ. Lick Observatory*, vol. iii. p. 211.

glow of its hydrogen constituent. Another pseudo-star in Aquila (N.G.C. 6891) disclosed itself prismatically to Dr. Copeland in 1884. It has a disc just 4″ across, and its spectrum, photographed by Von Gothard 27th October 1892,[1] includes the usual range of nebular lines up to λ 3727, besides a fair admixture of continuous light. A nebula of the fourteenth magnitude, visually a finished star, was noticed for the quality of its light by Pickering, 25th November 1881, near the star $b^2$ Cygni.[2] More conspicuous members of the class have been identified in considerable numbers on the Draper Memorial plates.

The crowd of small nebulæ photographed by Dr. Max Wolf in 1901 comprised a remarkable proportion of seeming planetaries. They were collected on his plates into pairs and groups in a manner recalling the distribution of Wolf-Rayet stars, but not previously observed to characterise that of planetary nebulæ. The question indeed arises whether they are really such? Or do they rather belong to "that much less interesting class of objects" designated by Mr. Burnham as "small circular patches of nebulosity"? The spectroscope alone can decide, and its verdict should be elicited without delay. Upon it will largely depend the conclusions to be drawn respecting the affinities of the planetary family, their mutual relations, and the mode of their scattering in space.

There is reason to believe them enormously remote. Four have been directly measured for parallax, namely, the helical nebula in Draco, the bi-nuclear planetary in Argo (N.G.C. 2440),[3] Webb's in Cygnus, and a structure with a ring and disc in Andromeda (N.G.C. 7663).[4] None showed the least sign of perspective shifting when viewed from opposite sides of the earth's orbit; and the demonstration thus afforded of their immense distance is confirmed by the insensibility of nebular proper motion. This, since it is continually progressive, must eventually prove determinable, and comparisons of its amount with the mean *radial* velocity of these bodies will supply a criterion for their absolute localisation. Pro-

[1] *Astr. and Astrophysics*, vol. xii. p. 52.
[2] *Observatory*, vol. v. p. 26.
[3] D'Arrest, *Leipzig Abhandl.* Bd. iii. p. 308, 1857.
[4] Wilsing, *Astr. Nach.* Nos. 3190, 3261.

fessor Keeler derived from the line-displacements in the spectra of eleven nebulæ a value for this quantity of sixteen miles a second; and by sixteen miles a second they should, accordingly, on an average, progress along each of the other co-ordinates fixing their position in space. When corresponding angular advances have been established, their average distance can then at once be estimated.[1] Let us assume, for instance, that the eleven nebulæ in question, taken one with the others, have a secular proper motion of three seconds of arc in declination, and as much in right ascension. This, although the outside of what is probable, implies that their mean distance corresponds to a light-journey of 580 years. A planetary not more than 10″ in diameter would, if thus remote, fill a globe about 600 times wider in girth than one circled by the orbit of Neptune, and 216 million times more capacious. The data supplied by Professor Keeler are indeed an obviously insufficient groundwork for extensive generalisations; but more of the same kind, and it may be hoped of not inferior quality, cannot fail to be forthcoming shortly; while the precise visual measurements executed by Burnham, Spitaler, Javelle, and others will surely serve, after some decades, for the detection of genuine nebular journeyings across the sky. A beginning of definite knowledge will then have been made regarding the true magnitudes and place in the sidereal scheme of these singular objects. It must not, however, be forgotten that many of the faint stars taken as fiducial points for their micrometrical determination may prove to be satellites of the neighbouring gaseous globes drifting and shifting in their company. This disquieting possibility, foreseen by Sir John Herschel and d'Arrest, would, of course, if realised, vitiate conclusions as to parallax or proper motion. Yet the work done for these purposes need not be looked upon as wasted. By its aid, should the slow revolutionary movements of stars round planetary nebulæ ultimately be brought to light, a new department of sidereal mechanics may be founded. Exact determinations in astronomy, made on a judicious plan, are rarely useless. If unprofitable for their designed aim, they are pretty sure to turn to account for some other, and perhaps a higher one.

[1] Kleiber, *Astr. Nach.* No. 3037.

# CHAPTER XXXV.

## ANNULAR NEBULÆ.

The model annular nebula is the beautiful filmy ellipse situated between $\beta$ and $\gamma$ Lyræ (N.G.C. 6720). Discovered by Darquier at Toulouse in 1779, it appeared to Sir William Herschel a simple hoop of light, quite dark within. The "gauze drawn over the hoop," spoken of by Sir John Herschel, had been perceived by Schröter in 1797, and with long exposures the photographed ring fills up into a disc. Plate XXV. is taken from a singularly perfect representation obtained by Mr. W. E. Wilson in twenty minutes, while an hour's exposure sufficed to blur beyond recognition the characteristic annular aspect of the structure. Yet the havoc thus wrought, in a pictorial sense, is compensated by the experimental significance of a result proving the interior of the ring to be far from vacuous of luminous or luminescent material.

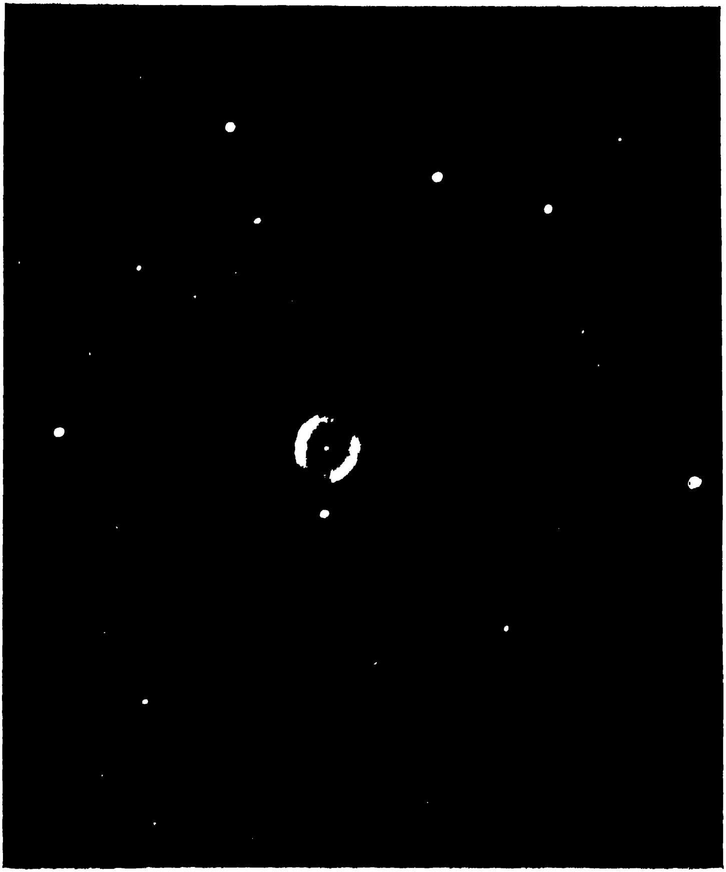
The dimensions of the ring are about 87″ by 64″. It was shown in the Lick negatives as an exceedingly complex structure. "It seems," Professor Keeler wrote,[1] "to be made up of several narrower bright rings, interlacing somewhat irregularly, the spaces between them being filled with fainter nebulosity." Many bright patches and condensations diversify the main annulus, which is, nevertheless, fundamentally continuous; it does not break up into detached knots of nebulosity. The light is strongest near the extremities of the transverse axis, and its failure at each vertex of the ellipse, conspicuously shown in our Plate, was, already in 1785, noticed by the elder Herschel.[2] It is accompanied by symptoms of

[1] *Astroph. Journ.* vol. x. p. 197.

[2] *Astr. Jahrbuch*, 1788, p. 242; *Phil. Trans.* vol. lxxv. p. 263.

P.

N.



S.

F.

The Ring Nebula in Lyra. Photographed by W. E. Wilson, F.R.S.
Exposure, 20m.

effusion, marking possibly equatorial outflows due to rotative acceleration. Lord Rosse in 1863, and Schultz in 1865, were alike struck with "nebulous radiations in the direction of the longer axis, which seemed momentarily almost to destroy the annular form." They issued from the north-eastern side, while a similar appearance on the south-westerly side of the nebula was observed by Professor Holden at Washington in 1875.[1] He perceived, too, with surprise that the south end of the minor axis, which Lord Rosse had represented as the best terminated, was unmistakably, after thirteen years, less clearly finished than the north end. Similarly, the Lick thirty-six-inch disclosed in 1888[2] the whole southern margin as filamentous, by a kind of alternation with the corresponding state of the northern edge noticed at Parsonstown. This tufted or fringed effect was caught, for the first time photographically, by Professor Keeler. The oval imprinted on his plates was fringed on both sides, and his measurement of eleven nebulous projections from it will give the means of detecting any future variations in their luminosity or distribution.

The gauzy stuff in the interior is not a mere formless light-mist. A drawing published by Lord Rosse in 1844[3] represented it as divided into longitudinal striæ, and their reality was confirmed by the Crossley photographs after fifty-five years. "I have tried," Professor Keeler wrote, "to verify this band-structure by visual observation with the thirty-six-inch refractor, and have fancied at times that I could catch glimpses of it; but the observation is a most difficult one, the contrast of the bright and dark bands, exaggerated by the photograph, being almost too slight to affect the eye." The surprising accuracy of the delineations made with the Rosse speculum, while its burnish continued unimpaired, was thus once more exemplified. It conveys a warning against lightly setting aside any of the earlier records concerning nebulæ obtained at Parsonstown, even when they imply seemingly improbable changes. It is certainly by no accident that the striæ within this nebula coincide in direction with its major axis; nor can the termination of the transverse axis by maxima,

[1] *Monthly Notices*, vol. xxxvi. p. 66. [2] *Ibid.* vol. xlviii. p. 387.
[3] *Phil. Trans.* vol. cxxxiv. plate xix. fig. 29.

of the longitudinal axis by minima of brightness[1] be regarded as casual features. All the details of the edifice, in fact, are arranged with obvious reference to its apparent shape, and this amounts to a demonstration that the elongation is real. The nebula, then, is not simply projected into an oval; it is not a circular formation viewed obliquely. There seems no escape from the conclusion that it is an ellipsoid of revolution—that the bands follow the line of the equator, and originate under conditions prescribed by the rotation of the body; while the partial interruption of luminosity at the ends of the oval mark outflows of matter where centrifugal velocity overrides the holding power of gravity. Everything, indeed, leads us to suppose that this nebula, like the rest of its kind, is actually a hollow spheroid of shining fluid, the marginal brightness resulting from the increased thickness of the luminous shell penetrated by the visual ray. The "hoop" and the "gauze" drawn round it are then two aspects of the same thing. Nebulous rings, as such, probably do not exist. They would be subject to perspective effects, no traces of which are to be found in the heavens. Annularity in nebulæ may accordingly be considered as a purely optical modification of a different structural plan.

A glittering point of light occupies the centre of the annulus in Lyra. Many anomalies are connected with its visibility. The first heard of it is in 1800, when Von Hahn of Remplin, in Mecklenburg, was surprised by its disappearance.[2] He attributed the change, not to loss of light in the star, but to the nebulous clouding-over of the black background upon which he was accustomed to see it relieved. Unperceived by the Herschels, it was next seen by Lord Rosse in 1848,[3] and attracted Father Secchi's attention at Rome in 1855.[4] A ten-inch Steinheil sufficed, in 1865 and 1867, even in unfavourable weather, to show Hahn's star to Hermann Schultz;[5] yet it unaccountably evaded the deliberate scrutiny, ten years later, of Professor Asaph Hall,[6]

[1] *Nature*, vol. xliii. p. 420.
[2] *Astr. Jahrbuch*, 1803, p. 106.
[3] *Trans. Royal Dublin Society*, vol. ii. p. 152.
[4] *Astr. Nach.* No. 1018.
[5] *Nova Acta Societatis R. Upsaliensis*, ser. iii. vol. ix. p. 99, 1874.
[6] *Astr. Nach.* No. 2186.

armed though he was with the twenty-six-inch Washington equatorial. The same instrument, however, displayed its evasive sparkle to Mr. A. C. Ranyard, 23rd August 1878;[1] while to Dr. Vogel, with the Newall telescope in 1875, and the Vienna twenty-seven-inch in 1883, it remained consistently imperceptible.[2] Very remarkable, too, is its non-appearance to Dr. Spitaler at Vienna in 1885, when he carefully delineated the nebula, as well as in 1886, during frequently repeated verifying observations.[3] The interior seemed then to contain only dimly luminous floccules; nevertheless on 25th July 1887 the star caught his eye at the first glance. It had, in the meantime, 1st September 1886, been photographed by Von Gothard, and has since abstained from capricious disappearances. It is indeed of such exceptional actinic power that the camera cannot easily lose sight of it. Fainter visually than the fifteenth magnitude, it needed only an exposure of one minute to come out distinctly on a Crossley negative, and it left a dim impression in half that time.[4] With all exposures the image was clearly defined, although in photographs taken with other instruments it had usually presented a hazy disc. Its light appears to be of normal stellar quality. Its maximum of intensity, that is to say, falls in the yellow part of the spectrum. Both Keeler and Barnard agreed that, with the Lick and Yerkes refractors, the focus for the star was about one-fifth of an inch shorter than for the encircling nebula. And a similar disparity exists between the nuclei and discs of most planetaries. This, however, leaves their special chemical effectiveness unexplained; for Keeler's suggestion of its being due to ultra-violet emissions lacks the support of known facts.

In the field with the Lyra nebula, Barnard perceived, 2nd October 1893, a second of about the fourteenth magnitude, 30″ in diameter, and somewhat irregular in shape.[5] Professor Keeler's longest-exposed negative showed the new object to be "a left-handed, two-branched spiral."

In 1891 Mr. Burnham measured the nucleus of the ring

[1] *Astr. Journ.* No. 200.
[2] *Potsdam Publ.* No. 14, p. 35.
[3] *Astr. Nach.* No. 2800.
[4] *Astroph. Journ.* vol. x. p. 199.
[5] *Astr. Nach.* No. 3200.

in Lyra with reference to an external star of the twelfth magnitude which closely follows it. Eight years later, Professor Barnard employed the forty-inch Yerkes telescope to repeat his determinations,[1] and was inclined to attribute a slight discrepancy to real motion in the nebula. But the Potsdam plates lent no confirmation[2] to a suspicion which will probably remain long unverified. His experience was entirely negative as regards light-variability in any part of the object. Alleged changes in the stellar kernel he translated into genuine changes in visual facilities. "The fact," he wrote, "that the nucleus is seen on a nebulous background makes steadiness of the atmosphere a most important factor in its distinctness—far more so than in the case of an ordinary star in the open sky. When the seeing is exceptionally good, the nucleus appears with a distinctness strikingly in contrast with its ordinary condition, so much so that one has to guard against deception in supposing a real change of light."

Nine bright lines have been seen or photographed in the spectrum of the Lyra annulus, that of shortest wave-length at λ 3727 being, according to Von Gothard, the most intense.[3] Hydrogen shines feebly; no C has been recorded, but the Rydberg ray at λ 4688 was detected by Campbell.[4] Helium is unrepresented; since a violet line at λ 3869, which appears prominently and persistently in nebular spectra, cannot be ascribed to that substance. It chances, indeed, to coincide approximately with one belonging to a known series, but is itself of "rare and strange" origin.

Several analogues of the Lyra nebula have been discovered; none so large or so bright. The best imitation is situated in Cygnus (N.G.C. 6894). It measures 47″ by 41″, the inner vacuity 20″, and was marked "resolvable" at Parsonstown.[5] Needless to say that the sparkling effect which conveyed the impression of a stellar constitution was altogether illusory. A fifteenth-magnitude star near the interior border of the ring to the north-west was measured by Burnham in 1891.[6]

[1] *Monthly Notices*, vol. lx. p. 245. [2] *Ibid.* p. 257.
[3] *Astr. and Astrophysics*, vol. xii. pp. 52, 55.
[4] *Ibid.* vol. xiii. p. 497. [5] *Trans. Royal Dublin Society*, vol. ii. p. 156.
[6] *Monthly Notices*, vol. lii. p. 44.

The true nucleus is considerably fainter. First brought to view in a photograph taken by Dr. Roberts 31st August 1897,[1] it duly reappeared in one of the Crossley pictures of 1899,[2] and was visually discerned with the great Paris siderostat by M. Antoniadi, 17th July 1900.[3] The elongation of the annulus from north-east to south-west was obvious to him no less than the faint haze with which it is filled. Nothing is known about the spectrum of the ring nebula in Cygnus. It doubtless resembles that of its prototype in Lyra.

Even more scanty is the information at hand regarding "a beautiful delicate ring" in Scorpio, about 40″ in diameter (N.G.C. 6337). It is in a field crowded with stars, two of which are projected upon, but may not belong to it. Neither occupies the proper position of a nucleus, and the one seen by Lassell at Malta had to him somewhat the aspect of a nebulous knot.[4]

An annular nebula in Ophiuchus (N.G.C. 6369) was found by Mr. Burnham "very like the well-known example in Lyra, except in brightness."[5] A central star of 14·5 magnitude was probably then first noticed. The longest diameter of the ring measures 31″; the edges seemed to Sir John Herschel "a very little cottony,"[6] and they are doubtless fringed with dim appendages, like those attached to its model in Lyra. This is again copied in an object discovered by Mr. Gale of New South Wales in 1897, or perhaps a little earlier. It is bright enough to make its late detection somewhat surprising.[7]

Immersed in a fine cluster in Argo (Messier 46), a nebula of planetary aspect, about 60″ in diameter (N.G.C. 2438), drew the attention of Sir William Herschel. The Rosse reflector showed a central star dominating a vacuous interior, besides two stars sparkling on the condensed border.[8] Lassell perceived in the object a resemblance to a large, dim, compound planetary in Eridanus (N.G.C. 1535), but with the

[1] *Celestial Photographs*, vol. ii. p. 133.
[2] *Publ. Pacific Society*, vol. xi. p. 180. [3] *Knowledge*, vol. xxiii. p. 250.
[4] *Memoirs Royal Astr. Society*, vol. xxxvi. p. 47.
[5] *Monthly Notices*, vol. lii. p. 38. [6] *Cape Results*, p. 114.
[7] Swift, *Pop. Ast.* December 1897, p. 426.
[8] *Phil. Trans.* vols. cxl. p. 513; cli. p. 716.

qualifying circumstance that in N.G.C. 2438 only one "stratum of nebulosity" was discernible.[1] This singleness of construction appears characteristic of perfected nebular rings, and such the inmate of the cluster in Argo has declared itself to be. In a photograph taken by Dr. Roberts, 24th February 1894,[2] it is definitely and unmistakably annular. Three stars are projected upon, or contained within it, we cannot tell which; although one by its nuclear position gives some assurance of being there through organic relationship. Nor can we venture to assert that the nebula is really *in* the cluster. It may only be thrown accidentally into line with it. Still the fact that Sir John Herschel recorded in two cases similar collocations of planetary nebulæ with clustered stars[3] inclines the balance of probability towards the side of genuine association. One of these groups (N.G.C. 5979) is situated in the constellation Circinus, the other (N.G.C. 2818) near the mast of Argo.

Certain complex formations, intermediate between planetary and annular nebulæ, have now to be considered. A striking specimen of the kind is met with in Andromeda (N.G.C. 7662). The disc, which includes perhaps more than one ring, measures 32″ by 28″. Alexander, about the middle of last century, and Lassell subsequently, thought the structure bi-annular. Vogel[4] and Holden remarked its warped and twisted appearance, denoting possibly a multiple combination of rings thrown off in various planes as the outcome of long-past crises in a slow process of development. A central star surrounded by close spirals of nebulosity was seen at Parsonstown,[5] but evaded the scrutiny of O. Struve in 1847, of Searle in 1866, and of Vogel in 1883. Lassell perceived it under the guise of a minute, bluish disc, Burnham as an ordinary fifteenth-magnitude star.[6] Fig. 4 in Plate XXIII. reproduces Professer Keeler's drawing of the Andromeda planetary with its visual spectrum.[7] "This nebula," he wrote, "is annular,

[1] *Memoirs Royal Astr. Society*, vol. xxiii. p. 60.
[2] *Celestial Photographs*, vol. ii. p. 35.
[3] *Cape Results*, p. 90, plate vi. fig. 7.
[4] *Potsdam Publ.* No. 14, p. 37.
[5] *Phil. Trans.* vol. cli. plate xxx. fig. 40.
[6] *Monthly Notices*, vol. lii. p. 46.
[7] *Publ. Lick Observatory*, vol. iii. p. 215.

with a bright inner ring and a very small nucleus. It is somewhat elongated north and south." The fourth line in the spectrum is the "fundamental" of Rydberg's hydrogen series; its unusual strength makes it the equal of the ordinary hydrogen lines on either side of it. The spectrum of the nucleus appears to be perfectly continuous, save for a possible bright knot about the place of $D_3$. Campbell, however, caught no glimpse of this radiation, although he determined, visually and photographically, eighteen bright lines in the spectrum of the nebula.[1] We subjoin his list, with notes and comments between brackets.

BRIGHT LINES RECORDED IN N.G.C. 7662.

| Wave-length. | Remarks. |
|---|---|
| 540 | Very faint, difficult (Wolf-Rayet line; Pickering series). |
| 532 | Very faint, difficult (possibly the chromospheric line K 1474). |
| 5007 | First nebular line, very bright. |
| 4959 | Second nebular line, very bright. |
| 4861 | Hβ, very bright. |
| 4744 | Faint (origin unknown). |
| 4715 | Faint (unknown). |
| 4688 | Very bright (Rydberg hydrogen line). |
| 4663 | Very faint (unknown). |
| 4643 | Faint (nitrogen ?) |
| 4472 | Very faint (helium; prominent in Orion stars). |
| 4364 | Bright (unknown). |
| 4341 | Hγ, very bright. |
| 4102 | Hδ, very bright. |
| 4067 | Very faint (unknown). |
| 4026 | Very faint (helium). |
| 3969 | Hε, very bright. |
| 3869 | Very bright (unknown). |

The brilliancy of the last line, in view of the faintness and fewness of other helium emanations, confirms the inference that its association with that substance is inadmissible. Experiments in the laboratory would nevertheless be valuable on the behaviour, for instance, of the adjacent violet line of helium in a mixture of that gas with hydrogen.

Campbell perceived this nebula to consist "of two nearly concentric rings more or less broken up, with a fourteenth-magnitude stellar nucleus near its centre." Ingall described

[1] *Astr. and Astrophysics*, vol. xiii. p. 499.

it, 18th December 1885,[1] as a "superb planetary," of a bright greenish-blue tint, the centre not quite dark, and thus fitly to be called annular. On applying a power of 500, "an extraordinary structure appeared to unfold itself. The bright ring seemed very jagged and fringed at the edges, and the centre was mottled with unequal shades, often as if of *two* dark centres." The note made on it at Harvard College was: "Somewhat annular; edges hazy."[2] The blue colour of the object faithfully corresponds to the actinic energy of its rays. In two seconds of exposure to them the Crossley reflector gave a weak image, including a barely visible central star,[3] and Professor Keeler obtained finished pictures in 20, 30, and 60 seconds. At Potsdam, in 1892-93,[4] thirty-three impressions were taken for the purpose of parallax-determinations, but they yielded no positive result. They afforded only the information that the nebula could not have an annual parallax so large as one-fifth of a second; and, indeed, the true value of the quantity, judging from other indications, may very well fall short of one-tenth the assigned maximum.

A "sky-blue likeness of Saturn" in Aquarius (N.G.C. 7009) is built very much on the lines of the Andromeda planetary, but with the addition of "ansæ." These, in August 1888, were resolved by Holden and Schaeberle, with the aid of the Lick refractor, into a pair of attendant nebulosities, situated in line with the major axis of a strongly elliptical body, and subsensibly united to it by evasive gleams of illumination.[5] Yet the likelihood is small of their being really satellite-globes revolving in the same track at an invariable interval of two right angles. The probabilities of the case oblige us to believe rather that the original interpretation of them as the extremities of an annular appendage came nearer the truth. An analogy indeed suggests itself between them and the nebulous effusions from the vertices of the ring formation in Lyra.[6] And here again we are assured that they

[1] *English Mechanic*, vol. xlii. p. 311.
[2] *Harvard Annals*, vol. xxxiii. p. 146.
[3] *Publ. Pacific Society*, No. 70, p. 201, 1899.
[4] Scheiner, *Astr. Nach.* No. 3086; Wilsing, *ibid.* No. 3261.
[5] *Monthly Notices*, vol. xlviii. p. 393.
[6] *Knowledge*, vol. xv. p. 149.

mark an equator—that the disc they seem attached to must be the projection of a rotating spheroid. Intricacies of interior arrangement are, however, visible, showing the progress of manifold activities. Two dark cavities, extended parallel to the major axis, and helical wisps of nebulosity, were observed by Vogel at Vienna in 1883.[1] Keeler saw and photographed a somewhat distorted condensed ring measuring 26″ by 16″,[2] and Scheiner's plates recorded curious spoke-like projections from an intensely actinic central star.[3] The spectrum differs from that of the Andromeda planetary only by the inclusion of the enigmatic "last line" at λ 3727. From the displacement of the green ray of nebulium Keeler determined for the Saturn nebula a movement of approach towards the sun at the rate of thirty-one miles a second, only a small proportion of which can be due to our own journey through space.

Sir William Herschel observed in the constellation Gemini in 1787 "a star of the ninth magnitude, with a pretty bright nebulosity equally dispersed all around" (N.G.C. 2392). Lord Rosse found in it a dark hole close to a slightly eccentric nucleus.[4] D'Arrest thought the object might be called annular;[5] Lassell perceived a ring surrounding a bluish disc;[6] Secchi described it as a star with an annular aureola.[7] H. C. Key, using an eighteen-inch silver-on-glass reflector, noticed about 1868[8] a concatenation of bright and dark rings besides the patch of interior obscurity detected at Parsonstown. To Burnham the nebula in Gemini appeared "one of the most beautiful objects of the kind in the heavens."[9] He assigned to it a diameter of 45.″ Barnard, finally, was impressed by its "magnificent and beautiful" effect in the Yerkes telescope.[10] It disclosed to him a ninth-magnitude star encircled not quite symmetrically by a brightish oval ring, partially incomplete towards the south. "This ring," he continued, "which is well defined inside and out, is surrounded by a vacuity, and this in

1 *Potsdam Publ.* No. 14, p. 38.

2 *Publ. Lick Observatory*, vol. iii. p. 213; *Astroph. Journ.* vol. x. p. 195.

3 *Astr. Nach.* No. 3086.

4 *Phil. Trans.* vol. cxl. p. 514, fig. 15.

5 *Abhandl. Leipziger Akad.* Bd. iii. p. 321; *Astr. Nach.* No. 1885.

6 *Memoirs Royal Astr. Society*, vol. xxiii. p. 61.

7 *Les Étoiles*, t. ii. p. 16.

8 *Monthly Notices*, vol. xxviii. p. 154.

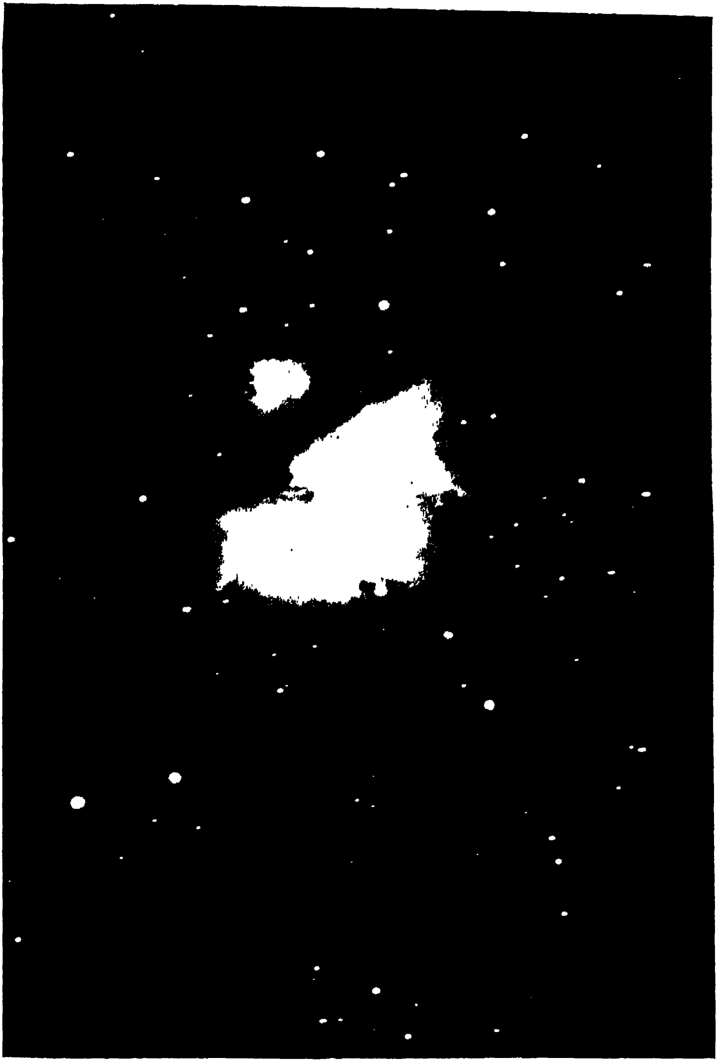
9 *Ibid.* vol. lii. p. 35.

10 *Ibid.* vol. lx. p. 256.

turn by an almost circular broad ring of light less intense than the inner ring, and with a distinct break in it north-preceding. It breaks up into a clouded or unequal surface, and is very irregular on its inner edge, but fairly uniformly circular on its outside edge. The inner ring is filled with a nebulous light which has a black spot in it, south-preceding the nucleus."

That the perforated effect is no illusion may be taken as proved. Nor is it subject to change. It has obtruded itself now for half a century upon one observer after another, under divers conditions, both instrumental and climatic. This nebula then, and a few others like it, betray the action of some force strange to our experience, by which the matter contained in an extensive region is either expelled thence, or its light-giving faculty suppressed.

The annular nebula in Lyra is the only member of the class that has been satisfactorily investigated. Until spectrographic possibilities are further developed there seems little chance of dissipating the perplexities that still envelop its nature. That is, by direct means; for indirectly much may be done. Comparisons, for instance, of detailed results for sister-objects ought to prove highly instructive as to the laws governing the construction of all alike. Most of them have been singularly neglected, considering the interest attaching to their peculiarities. The hooped nebula in Cygnus, the "ghost" in Scorpio, Gale's annulus, the ring in Ophiuchus, should be photographed with long exposures, on a scale sufficiently large to bring into view specialties of texture and build. Their agreement in certain fundamental relations would thus be tested, and its importance as a guide to theories of their mode of origin cannot be overrated. Their self-delineation would, however, doubtless accentuate besides that variety in similarity which, throughout the whole created world, illustrates the wealth of the resources disposed of by Nature, and the inexhaustible inventiveness of the Mind revealed in Nature.



Photograph of the Orion Nebula (W. H. Pickering)

# CHAPTER XXXVI.

## THE ORION NEBULA.

THE first place among irregular nebulæ is, by universal consent, accorded to the gleaming formation in the Sword handle of Orion. Although incidentally referred to by Cysatus of Lucerne in 1618, it received little attention until Huygens, in 1656, affixed his note of admiration, and executed a drawing of the bright central part, still known as the "Huygenian region." Here is situated the trapezium, the hub, as it might be called, in which all the spokes of the great wheel are inserted. A photograph of the group is reproduced in Plate XXIV. Fig. 2. It was taken by Professor W. H. Pickering from Mount Wilson, California, 29th September 1889, with the thirteen-inch Boyden telescope. The exposure allowed was only ten minutes, and already the enveloping haze was beginning to cloud the images of the stellar sextett. The companions (which seem to vary in light[1]) of the two brighter stars are distinct in the original negative, and can be made out in the figure, one as a tiny blotch, the other as a mere deformation of the lowest and largest disc. The physical association of these six stars may be assumed without much risk of error; but there is nothing to show that any real tie exists between them and four adjacent star-points, at the limit of vision with the Lick thirty-six-inch, detected by Barnard and Alvan Clark in 1889.

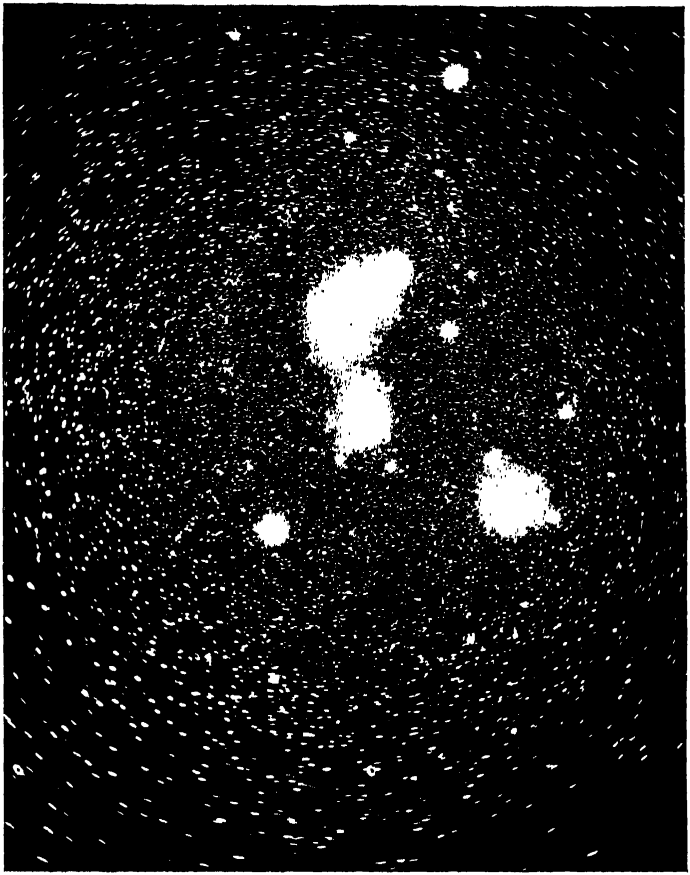
The nebula, as it developed on a plate exposed, under the same circumstances, during $2^h$ $36^m$, is shown in Plate XXVI. The stars of the trapezium are here completely submerged; only their influence can be traced, or suspected, in the

[1] Comas Solà, *Astr. Nach.* No. 3751.

symmetrical arrangement of the expansive wings of light stretching away from their place. These are by no means vague or indefinite outflows. Some of the long streamers have sharp inner edges, peculiarly curved and notched. And the texture is generally filamentous, like that of solar prominences, the characteristic forms of which—as Mr. Ranyard effectively pointed out [1] are faithfully imitated in some of the minor features of the nebula. An outlying mass to the north (N.G.C. 1977) not only claims affinity by some degree of structural resemblance, but is seen, on Professor Pickering's plate, to be linked on to it by a faint intermediate extension. The gap between them is absolutely black to telescopic vision.

Improvements and modifications in photographic methods have led, by successive steps, to a remarkable increase in the compass assignable to this extraordinary formation. Portrait-lenses have played a leading part in the process. Professor Wadsworth's reasonings [2] have made it clear that small apertures, owing to the greater contrast afforded by them with the sub-sensible illumination of the sky, are positively advantageous for obtaining impressions of faint, extended objects. They have the further prerogative of a wide field of view, giving room for the grasp and delineation of large contours; so that, in certain branches of celestial portraiture, they render indispensable and invaluable services. By their aid the nebulous stars $\iota$ and $c$ Orionis were proved to be dimly connected with the trapezium nebula; a sharply indented streamer became apparent, issuing towards it from the belt star, $\zeta$ Orionis, long recognised as a separate focus of nebulosity; while Max Wolf derived evidence of a luminous union between the nebulæ surrounding $\zeta$ and $\epsilon$ Orionis.[3] Finally, the combined picture, shown in Plate XXVII., of all the nebulous patches in the constellation was obtained by W. H. Pickering, 14th January 1890.[4] The instrument employed was a Voigtländer lens, 2·6 inches in aperture, and of 8·6 inches focal length; the time of exposure, $6^h\ 22^m$. As the upshot, the fragmentary condensations previously known became united into a vast spiral formation, 15° across. Starting from near Bellatrix (which lies outside the field), it sweeps round by $\kappa$ Orionis and Rigel to the

[1] *Knowledge*, vol. xii. p. 147.
[2] *Ibid.* vol. xx. p. 193.
[3] *Astr. Nach.* No. 3027.
[4] *Harvard Annals*, vol. xxxii. p. 66.



Nebulous Formation in Orion. Photographed, 14th January 1890, by W. H. Pickering.

south, then bends upward to $\eta$ Orionis, and most probably effects a junction with the nuclear mass in the Sword handle, although the further course of the stream is rendered indistinct by the fogging of the plate. After an interval of nearly five years, Professor Barnard independently repeated and confirmed the Mount Wilson experiment.[1] His small "lantern lens" showed, with exposures of $2^h$ and $1^h\ 15^m$, "an enormous curved nebulosity encircling the belt and the great nebula, and covering a large portion of the body of the giant." In comparison with it, he remarked, the old trapezium nebula "is but a pygmy." The astonishing extension given to the luminous structure in Orion was, however, of less importance than the disclosure of its architectonic plan. Nor can it be supposed that we are, even now, fully acquainted with it. Further developments may be looked for. The nebulous connections of the various parts will doubtless be more clearly expounded in future photographs. Possibly an effective delineation might be obtained in sections with instruments, like the Crossley or the Meudon reflector, too restricted in angular grasp to embrace the whole at one view. The study of details would thus be made feasible, their subordination to the general design being at the same time kept well in sight. The relations of the members to the main body of this nebula offer a problem of extreme complexity. The stars of the trapezium, for instance, have an appreciable proper motion of about $5''$ a century. The nebulous plumage attached to them must evidently partake in their displacement; but this cannot be unhesitatingly asserted of the appendages to the belt stars, still less of the ocean-river of nebulosity flowing outside them. Professor W. H. Pickering discussed the movements of nineteen stars involved in the spiral, though not of course necessarily connected with it.[2] And so far as any common character could be ascribed to them, it was that of recession from the trapezium. It would be ridiculous to found any conclusion upon so flimsy a basis; yet the indication harmonises with hints, or nascent symptoms of a centrifugal tendency among clustered stars such as the Pleiades. The determination and comparison of their radial movements will be the best means of promoting

[1] *Astr. and Astrophysics*, vol. xiii. p. 813.

[2] *Harvard Annals*, vol. xxxii. p. 77.

knowledge on the subject; and since Pickering's nineteen stars are all, except one, brighter than 6·2 magnitude, their spectroscopic measurement should present no difficulty.

Meanwhile the original "Fish-mouth" nebula raises, even when treated apart, questions of extreme intricacy. Seventy of the stars scattered through it were photographically determined by Scheiner, and compared in 1898[1] with Gould's similarly deduced places for them. The close agreement of the results showed them to have remained sensibly stationary during about a score of years, not sharing the drift of the central group. They must accordingly become, in course of time, detached from it, and from the encircling nebula. They constitute then no physical part of the structure, but are scattered casually over its surface. The trapezium-stars, on the contrary, are really embedded in the nebula. And the grounds for this assertion are two-fold. Visual logic by itself certifies its truth. The wings of a bird do not start more definitely from the breastbone than the nebulous plumes from the stellar group at their base. The relation is emphasised by the circumstance that two of its members serve as the abutments of a luminous arch, photographed at Potsdam,[2] which spans the interval between them. A similar nebulous bridge was remarked by Dr. Scheiner, to connect two other stars in the outskirts of the formation. Then, as we have already seen, the spectrum of $\theta$ Orionis presents peculiarities indicative of a close affinity with the nebulous masses around, and indeed suggests, albeit doubtfully, an actual commingling of luminous substance. It follows that the nebula shares the proper motion of the stars, the small secular value of which (5″), at the probably vast distance of the involved objects, corresponds to a very considerable real velocity. Admitting for a moment the correctness of Professor Pickering's estimate of one thousand years for the duration of the light-journey from the Orion nebula hither,[3] we should have to ascribe to the trapezium and its belongings a lateral speed of forty-nine miles a second, the greater part of which would be inherent, since its direction precludes the supposition that it is a perspective effect of the solar journey. The receding

[1] *Astr. Nach.* No. 3513.
[2] *Jahrbuch der Erfindungen*, 1898, p. 101; *Potsdam Publ.* Bd. xi.
[3] *Harvard Annals*, vol. xxxii. p. 80.

radial motion of eleven miles per second, determined for the nebula by Keeler, seems, on the other hand, to belong almost entirely to the sun. Yet the line-displacements by which it is indicated vary, in some degree, from tract to tract of the formation. Recent spectrographic measures executed at Potsdam[1] imply the progress of interstitial movements, the nature and laws of which it will be of the highest interest to ascertain.

Thirty bright lines, from λ 5007 up to the seventeenth member of the hydrogen series, have been photographed in the spectrum of the Orion nebula, besides the baffling groups faintly apparent on the Tulse Hill plate of 1888. The yellow helium ray ($D_3$), visually detected by Dr. Copeland in 1886, has at least three more refrangible associates; but several lines met with in planetary nebulæ are missing, notably those distinctive of the Wolf-Rayet class of stars. Thus the Pickering and the Rydberg series are alike unrepresented in this grand object. Nor does it glow with the light of any metallic vapour. Its hydrogen emissions are in some respects peculiarly conditioned. The red line is invisible; the green and blue lines are especially bright; beyond them there is a progressive decrease of intensity, though the complete series, up to $H\rho$, was photographed by Mr. S. A. Mitchell, with a concave grating of 11½ square inches, mounted on the twelve-inch refractor of the Yerkes Observatory.[2] Thus the state of the nebula is such as to favour, apparently, the development of the quicker luminous vibrations. The inference has, indeed, been controverted. Dr. Scheiner maintained that the suppression of C in this spectrum is "due to purely physiological causes, and warrants no conclusions as to the physical conditions of luminosity," in nebulæ.[3] He regarded it, in fact, as an illustration of the "Purkinje effect," by which the eye, owing to its differential colour-sensitiveness, loses sight of a red sooner than a green ray, when the light-source from which both proceed is gradually enfeebled. In the laboratory, accordingly, F survives alone in the spectrum of a hydrogen-tube at minimum illumination. The plausible deduction that there is no objective reality in the anomalous variations of comparative strength affecting the hydrogen lines derived from celestial objects is, nevertheless, untenable. It

[1] Vogel, *Sitzungsberichte*, Berlin, 13 März 1902.

[2] *Astroph. Journ.* vol. x. p. 29.

[3] *Astr. Nach.* No. 3476.

collapsed hopelessly, on being confronted with the simple fact, noted by Keeler,[1] that the third hydrogen line ($H\gamma$) always vanishes experimentally before the first, while in nebulæ it shines unfailingly, although F be imperceptible. The order of brightness, then, of the members of the series is not, in nebulæ, prescribed by physiological causes alone; the faintness of $H\alpha$ is intrinsic. This is further proved by Professor Keeler's observation of "$H\beta$, and several of the hydrogen series above it, glowing brilliantly in the spectrum of R Andromedæ, while not a trace of $H\alpha$ could be found." So that "in some of the variable stars we seem to have hydrogen in the same condition as in the nebulæ."

Finally, Professor Campbell made the decisive experiment of directly comparing the nebular with an artificial spectrum.[2] The two kinds of light being admitted through the upper and lower halves respectively of the same slit, their spectra were seen side by side in the eyepiece, and the corresponding lines in them could be at once equalised by merely altering the distance of the hydrogen-tube from the slit. Combined experiments with this apparatus by Keeler, Wright, and Campbell proved that (1) when the F lines from the nebula and tube were matched in brightness, the blue line above it ($H\gamma$) was markedly stronger in the nebular than in the tube-spectrum; (2) the equalisation of the blue lines left the green line from the nebula conspicuously fainter than the same line from the tube. "The relative intensities," it was concluded, "of the hydrogen lines from the nebula and from the tube are, therefore, not the same; the nebular lines are relatively the stronger toward the violet, the lines from the tube are relatively the stronger toward the red end of the spectrum." Absolute measures showed the three principal lines in the spectrum of the Orion nebula to be of very low intensity. Their faintness completely neutralised, to Professor Campbell's eye, their differences of tint. Hence the "Purkinje phenomenon," which depends upon the perception of colour, cannot in any degree affect their comparative visibility. There is, however, another aspect to the question. The spectrum of the nebula varies, not alone from the standard of comparison supplied by the

[1] *Publ. Lick Observatory*, vol. iii. p. 224.
[2] *Astroph. Journ.* vol. ix. p. 312.

vacuum-tube, but also locally, within the formation itself. The relative strength of the constituent rays is different for its different sections. Dr. Runge of Hanover,[1] who devoted special attention to the point during a visit to the Lick Observatory in September 1897, satisfied himself that the F line of hydrogen, which, near the trapezium, had only one-third (or possibly two-fifths) the intensity of the nebulium line, was ten times brighter in the faint outlying sections of the nebula. The relative gain was then twenty-five to thirty-fold; while the alleged physiological cause, admitting that it had full scope and play, could at the utmost have produced a gain of 1·8 times. The reality of the change was further certified by observing the second nebular line ($\lambda$ 4959), which in the "Huygenian region" just equals F, to disappear as the slit was moved outward, while F continued to shine with a very sensible lustre. And since, in this case, the Purkinje effect was null (the lines being almost indistinguishable in colour), a demonstration was afforded of a genuine modification in the curve of emissive energy in passing from one part of the great nebula to another.

Professor Keeler devised a completely novel method of demonstrating its non-homogeneous character.[2] Pictures of the nebula taken on orthochromatic plates protected by colour-screens from the blue radiations, were compared with impressions on ordinary unscreened plates, all being exposed with the Crossley reflector, though during very unequal times. The result was to show that, for equal intensity of the Huygenian region, that of the remote parts and outlying streamers fell greatly below its normal value in the screened photographs. "Conversely," to quote the words of the ingenious operator,[3] "where photographs made by the two methods, on the same night, show an equal extent of nebulosity, the Huygenian region is very much more intense on the orthochromatic plate. We infer, therefore, that in the remote parts of the nebula the two lowest nebular lines are weak, or the hydrogen lines strong, as compared with the Huygenian region. Thus the results of spectroscopic researches are confirmed, and are extended to parts of the nebula too faint for visual observa-

[1] *Astroph. Journ.* vol. viii. p. 32; *Astr. Nach.* No. 3471.
[2] *Astroph. Journ.* vol. ix. p. 133. [3] *Ibid.* p. 140.

tion." That is to say, the hydrogen image of the Orion nebula is larger than its image in nebulium. And this corresponds precisely with Campbell's spectroscopic discovery about the planetary nebula S.D. – 12° 1172,[1] already adverted to. When nebulium comes to be examined in the laboratory—if that shadowy possibility be ever realised—the cause of the discrepancy may be laid bare. The most obvious is a difference of density between the two substances; yet we cannot unreservedly assume its validity, considering the noted effects of what we may call electrical preferences in modifying the spectra of attenuated gaseous structures.

Two facts, then, have been definitely ascertained regarding the hydrogen spectrum in the "Fish-mouth" nebula. The first is that its more refrangible constituents are preferentially developed as compared with the standard set by the vacuum-tube. The second is that of its persistence in regions of the nebula too dim to glow with any other species of light. Both peculiarities urgently demand explanations, which can probably be afforded only by arduous experimental work. Dr. Scheiner has not neglected this side of the inquiry; and although the outcome of his efforts is negative, it serves none the less to answer a fundamental question. He postulates in nebulæ extreme rarefaction and excessively low temperature; and to test the effect of the latter condition he plunged hydrogen-tubes into liquid air and examined the spectrum. He found it entirely unchanged by cooling to – 200° centigrade.[2] This, he pointed out, harmonises with the view that the luminosity of gases originates solely through internal movements of the individual molecules, and is hence independent of external temperature. Moreover, one of the few means available for terrestrially altering the relative strength of the red and green hydrogen lines is that of electrical differentiation. Professor J. J. Thomson's observation[3] of C bright, F invisible near the positive, F bright, and C invisible near the negative electrode, offers a clue which has not yet been followed up, for the threading of the labyrinth.

In another of its elements besides hydrogen, the spectrum of the Orion nebula is suspected to vary regionally. The

[1] *Publ. Pacific Society*, vol. v. p. 207. [2] *Astr. Nach.* No. 3476.
[3] *Proc. Royal Society*, vol. lviii. p. 255.

ultra-violet ray at $\lambda$ 3727 is second to none in importance when photographed with suitable apparatus. Nevertheless, it was missing from a plate exposed by Sir William and Lady Huggins 28th February 1889,[1] although the impressions upon it of two much weaker lines near its place were clearly to be seen. The anomaly of its total absence has not recurred. Professor Keeler vainly went over the ground in 1892-93,[2] groping with his slit for the blank district. Professor W. H. Pickering, it is true, derived indications of local diversities in the intensity of the line from a photograph taken without a slit, 10th July 1888; but they were rather suggestive than conclusive.

Suspected light-variations in the Orion nebula have not been confirmed by modern research. There is absolutely no photographic evidence of change, and visual discrepancies have not been attested with sufficient precision for the support of any positive inferences. Professor Holden was indeed disposed, after an exhaustive comparison of his own with numerous recorded observations, to believe in luminous instability of a partial kind;[3] but the effects considered may have been only apparent. Their production is at once rendered intelligible by Professor Ormond Stone's pertinent remarks:—"The general appearance of the Huygenian region," he wrote in 1896,[4] "is very much like that of a so-called 'mackerel sky.' Many of the condensations have pretty well-defined nuclei, whose light diffuses, blending with the surrounding nebulosity when the seeing grows poor. I have frequently been surprised to find how greatly the definition changes the relative brightness of the different condensations. This explains the many apparently contradictory estimates." So far as it is possible to judge, then, the brightness of this nebula is not subject to change, either general or local. Moreover, its component parts seem absolutely fixed in outline and position. Internal movements, if in progress, will need the lapse of ages to become sensible to the eye. No relative shiftings of knots or nuclei have been detected; no alteration in shape

[1] *Proc. Royal Society*, vol. xlvi. p. 41.
[2] *Astr. and Astrophysics*, vol. xiii. p. 478.
[3] *Washington Observations*, 1878, App. i.
[4] *Publ. Leander M'Cormick Observatory*, vol. i. pt. vii. p. 274.

of outgrowths and effusions. Yet they are of an eminently unstable aspect, and might be supposed no less essentially transitory than the appurtenances of comets. And so most probably they are, although the unit of time by which their duration is measured be long, and the scale of their construction unimaginably vast.

Some of the stars, however, scattered near the trapezium preserve anything but a constant lustre. One, catalogued as T Orionis, fluctuates irregularly from 9·7 to 13·0 magnitude; and others vary as unmistakably, though to a less extent. None are periodical, so that they belong to a different category from the flash-lights of globular clusters. An attentive study, photometric, photographic, and spectroscopic, of the Orion variables could not fail to be fruitful and instructive. Their instability is the more noteworthy from the whiteness of their light. T Orionis (also known as "Bond 822") is perhaps a unique example of a star untinged with red losing and regaining nineteen-twentieths of its visible radiance. Among its obviously variable neighbours are the objects numbered by Bond in his survey of the nebula, 641, 647, 654, and 679. Scarcely any sustained attention has yet been paid to the group, notwithstanding the many questions of interest connected with it. Enough only is known to make it certain that its members exhibit no community of character in their vicissitudes save that of exemption from any traceable law of order. Thus Bond 654 was noticed by Holden, as it had been noticed by Otto Struve twenty years earlier, to rise occasionally, from habitual quasi-extinction, to brief maxima of about twelfth magnitude. But Ormond Stone recorded none of these sudden brightenings, although he observed the star, 30th September 1886, to rank higher than the twelfth magnitude. Possibly the manner of its variability is itself variable. The star Bond 647, on the other hand, has gained largely in average lustre since 1837, when Sir John Herschel's measures, reduced to Struve's scale, made it of 13·1 magnitude. Otto Struve chronicled its disappearance in 1863, after a prolonged maximum at 12·5 magnitude;[1] Bond found it to be of 11·6 magnitude in 1867;

[1] *Mémoires de l'Acad. de St. Pétersbourg*, t. v. No. 4, p. 115.

Ormond Stone, of 10·9 magnitude, 1886 to 1894;[1] and there is nothing to show that this steady rise has reached its culminating point. A compensatory decline may be anticipated, though not with entire confidence. The situation of these stars lends a special meaning to their variations. That they are physically connected with the nebula they are seen projected upon, cannot indeed be proved, but it may legitimately be assumed. Hence every advance in knowledge of their vicissitudes cannot but help to elucidate the still obscure relations of nebulous environment to stellar light-change.

[1] *Publ. Leander M'Cormick Observatory*, vol. i. p. 333.

# CHAPTER XXXVII.

## OTHER IRREGULAR NEBULÆ.

IRREGULAR nebulæ are objects of large size, indeterminate outlines, and capricious shapes. They become fully apparent, as a rule, only by photographic means, their exterior sections and subordinate parts shining too dimly for distinct visual perception. The chemical retina, however, sees them with comparative ease; for their light consists mainly of isolated short-period vibrations. They are hence known to be of gaseous composition, and all are situated in or near the Milky Way. Many observers, especially those armed with large reflectors, can pick them out at sight by their greenish tinge; but they never appear blue like planetaries. There seems, indeed, to be a definite difference of hue between the two classes, approximate spectral identity notwithstanding. This probably indicates superior strength of the nebulum lines in irregular nebulæ; or the maximum of intensity in the dim continuous spectrum may be situated lower in them than in the planetary kind. Discrimination is not easy; for impressions of colour are often too subtle to be analysed.

Irregular nebulæ are of surprising variety. Each specimen has individual peculiarities, for the most part inimitable by any other. No copy of the Orion nebula is to be found in the heavens, and the Argo nebula, which comes next to it in importance, is equally *sui generis*. This magnificent edifice has no corner-stone corresponding to the trapezium; instead, a black opening of a lemniscate form, and as sharp to the eye as if cut with a punching instrument, yawns in its brightest part. The operation by which it came to be produced was, moreover, repeated in a fainter nebulous tract

farther south, and was hence evidently controlled by some definite and special combination of circumstances. With reason, then, in view of the unique character of this feature, the formation has been surnamed the "Key-hole Nebula."

At the eastern edge of the northern key-hole lies the extraordinary variable, $\eta$ Carinæ, the vicissitudes of which cannot but be related to the tumultuous processes of change doubtless going on in the seething chaos around. The general surface of the nebula is emblazoned besides with a multitude of ordinary small stars, historically and telescopically undistinguished. Their scattering, however, is not at random; it has marks of *intention*. Sir John Herschel pointed out their disposal along the margins of dark rifts in the nebula; and many such allineations were traced by Mr. Ranyard[1] in Dr. Russell's photographs, taken at Sydney in 1894. The object as a whole seemed to him "a very fine specimen of a nebulous cluster with a central condensation, associated with dark structures and radiating streams of stars." These "are in most cases accompanied by narrow black channels in the general nebulosity, which run parallel to, and alongside of the star-streams." One is reminded of the dark lanes bordered with stars in the Hercules cluster; and the analogy, if genuine, is of no slight significance. Setting aside for the moment its implications of affinity between stellar globes and nebulæ, it would afford a certainty that the stars distributed over the surface of the Argo formation are really in and of it; and since they are obviously galactic, this would amount to a demonstration that the nebula too is galactic—that it belongs to the Milky Way, not geometrically by projection, but physically by collocation.

The first photograph of this fine object was obtained by Dr. Russell with a six-inch portrait-lens in June 1891; but it had an experimental rather than a delineative value. This could not be said of one taken nine months later by Sir David Gill. An exposure of twelve hours, spread over four nights, with the thirteen-inch photo-refractor of the International Survey, yielded the remarkable picture which forms our frontispiece. The advantages of the autographic process could not be more forcibly exemplified than by comparing it with

[1] *Knowledge*, vol. xvii. p. 133.

Sir John Herschel's drawing of the same object.[1] Months of labour at the telescope were of less avail than half a day's "following" with the camera. The artist fully recognised the inability of even his skilful hand to delineate the endless gradations of light and shade which his eye perceived. The elaborate pains taken by him tended, indeed, as in most similar cases, to exaggerate contrasts, and so vitiate the general effect. In the photograph, the disclosed nebulous fields are not only wider, but they are more harmoniously related and more intelligibly arranged. Nor has the distinctive trait of the nebula evaded chemical portraiture. The "key-hole" is conspicuous on the plate, although deformed by luminous inflows; Herschel's "kidney-bean" opening to the south (sixth square from the bottom, fourth from the left side of the Plate) is scarcely encroached upon by chemical diffusion; and a third vacuity of similar design, though less perfect execution, occurs to the north-west of the key-hole (fourth square from the top, seventh from the left). There is, nevertheless, one striking discrepancy between the drawing and the photograph —a discrepancy which, on the face of it, implies the occurrence of genuine and extensive change. An isolated, trident-shaped structure prominent in the former is imperceptible in the latter, or survives, at the most, fragmentarily. Its disappearance was due to no accidental defect in the Cape negative; the Arequipa plates, exposed with the Bruce twenty-four-inch lens, show a corresponding effacement. It had, in fact, taken place even to the eye already in 1871, when Dr. Russell failed to perceive the "swan" form (as Sir David Gill called it) with the Sydney eleven-inch refractor. The evidence of light-extinction is almost conclusive; yet it should not be admitted without further question. Visual study of the nebula would perhaps be the most promising road towards the end in view. Such objects are now rarely *looked at;* observers adapt their apparatus and devote their energies to the exposure of plates. Yet in some cases—and this is surely one of them—the direct and indirect methods should, for completeness, be employed concurrently. Photographic and photometric brightness are commonly disparate in stars; they differ in nebulæ still more widely; it remains to be

[1] Copied in *Knowledge*, vol. xvi. p. 69.

proved whether their differences may not be irregularly distributed or even variable with time. The spectrum of the Argo nebula is of the usual gaseous type. Further particulars about it are wanting.

The Trifid nebula in Sagittarius (M 20 = N.G.C. 6514) affords another instance of ostensible change. Discovered by Messier in 1764, it appeared to Sir William Herschel in 1784 in the guise of "three nebulæ faintly joined into a triangle. In the middle," he added, "is a double star." And again, after two years, "About the double star is a black opening," the combined effect of which recalled the Orion trapezium. He reiterated in 1811 that the position of the star was "in the middle" of the obscure space between the nebulæ.[1] Sir John Herschel similarly assigned its place in 1827[2] as "exactly in the central vacuity of a large irregular nebula, which appears to have been broken up into three portions by three rifts or cracks extending from its centre to its circumference, and whose directions meet at the double star." Nothing could be more explicit; and his verbal description is authenticated by a rough sketch of high evidential value, though laying no claim to precision. Six years later, at Slough in 1833, he observed the double (really a sextuple) star to occupy "the centre of the trifid nebula." Yet at the Cape in 1835, he drew it as adhering to the south-eastern lobe, and—stranger still—without comment on the alteration. And virtually under the same aspect the object was seen by the American observers, Mason and Smith, in 1839, as well as by Lassell at Malta in 1862. The complete immersion of the star-group in nebulosity, and its eccentric situation at the apex of a shining conical mass, are now patent to the merest tiro in telescopic scrutiny. Autographic impressions tell the same tale. One obtained by Dr. Roberts in ninety minutes, 13th July 1899, is shown in Plate XXVIII. Fig. 1. The open fan of nebulosity in the south-eastern quadrant has the multiple star at its apex, but indistinguishably, owing to the burnt-up condition of the plate in this bright region. The abruptness with which the luminous

[1] *Phil. Trans.* 1786, p. 494; 1789, p. 247; 1811, p. 289; quoted by Holden, *American Journ. of Science*, vol. xiv. p. 434, 1877.

[2] *Memoirs Royal Astr. Society*, vol. iii. p. 63.

masses abut upon the dark rifts that divide them is most remarkable. On a Crossley plate of 6th July 1899,[1] the small central block of nebulosity came out semi-detached, while in the Crowborough picture it appears as a simple prolongation of the great northern lobe. Here, too, by a further effect of light-concentration, the dependent nebula to the north is completely annexed by the adjacent triple structure. Its nuclear star would make an interesting subject for spectroscopic study.

Now Herschel's Cape drawing of 1835 is in substantial agreement with the photographs of 1899. He saw about the same extent of nebulosity disclosed in them, distributed very much in the same way, and similarly related to the principal stars scattered through it. During sixty-four years, at any rate, fixity has prevailed. Mutual displacements are not sensibly in progress. The alleged variation must, we are driven to infer, have taken place suddenly between 1833 and 1835. This is certainly hard of credence; but it is still more difficult to admit that both Sir William and Sir John Herschel erred so egregiously as to locate the multiple star in the middle of a black space, if it really sparkled, as it does now, upon a background of lucent silver.

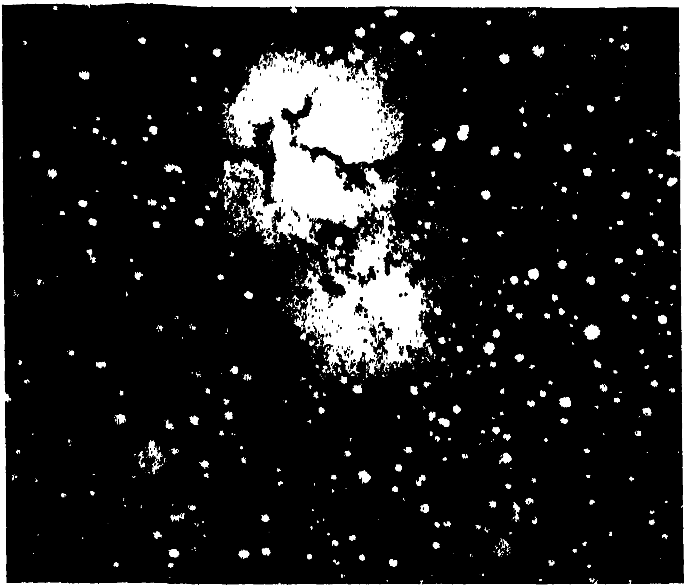
Professor Swift mentions having observed about 1888 "a luminous filament of the most delicate spider-like fineness stretched across the north-west cleft" of the Trifid nebula.[2] It reminded him of a cable of the New York and Brooklyn suspension bridge, with the difference that it did not sag in the middle, but went straight from shore to shore. The installation of electric street lights at Rochester precluded him from keeping watch over this delicate and perhaps novel feature. It would be interesting to learn whether it continues visibly to span that strange abyss.

The spectrum of this nebula was observed by Professor Keeler in 1890 as "continuous but short, being apparently confined to the blue and green."[3] Only a "brightening near the middle" could be detected. Nevertheless, on 3rd August 1894, Professor Campbell perceived at a glance the three

[1] Reproduced in *Astroph. Journ.* vol. xi. p. 325.
[2] *Popular Astronomy*, vol. i. p. 251.
[3] *Publ. Lick Observatory*, vol. iii. p. 205.

South.

1. West.

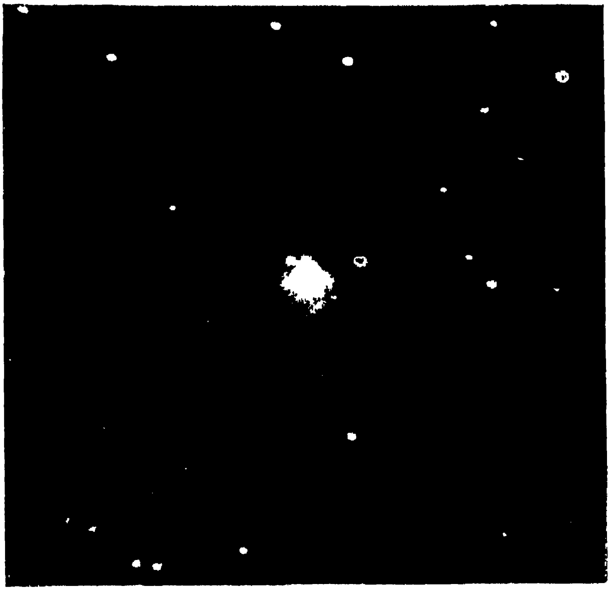


East.

North.

S.

2. P.



F.

N.

1. Photograph of the Trifid Nebula. Taken by Dr. Roberts, 13th July 1899.
2. Photograph of Messier 77. Taken by Dr. Roberts, 26th November 1892.

usual nebula lines, the third (F) being relatively strong.[1] An auroral glow almost effaced whatever continuous light was present; and the same accident, singularly enough, recurred at the date of a second observation 24th May 1895. Much might be learned about the nature of the Trifid nebula by a searching spectrographic inquiry. The condition, for instance, of the unknown line at $\lambda$ 3727 would be important to ascertain. Its variations from one object to another, or possibly from one region to the next of the same object, are doubtless of a significance only to be fathomed by the patient collection and comparison of facts. The spectrum of the multiple star, which seems to have a nuclear relation to the south-eastern division of the nebula, was stated by Keeler to be devoid of marked features. Yet such may present themselves when its thorough examination becomes practicable. The components of the object were successively discovered in the course of nearly a century. Sir William Herschel saw it double in 1784; Herschel and South about 1826 found it to be triple; and no more than three members of the group were distinguished by Lassell with his four-foot reflector. The fourth and fifth stars—neither much brighter than the thirteenth magnitude—were added by Professor Langley, using the fifteen-inch Harvard College refractor, in 1866; finally, the Washington twenty-six-inch disclosed the sixth to Professor Holden 5th August 1875.

A fantastic structure, known as the "Omega" or "Horse-shoe" nebula (M 17 = N.G.C. 6618), is situated on the border of Scutum Sobieski, and, like the Trifid, invites inspection from southern latitudes. Sir John Herschel perceived it at Slough in the figure of a Greek Omega ($\Omega$), with the left-hand base-line turned upward.[2] He was surprised to see at the Cape a second arch springing from the same level as the first,[3] besides other suspected convolutions. The subordinate appendage was again noticed by Swift in 1883.[4] In a photograph taken by Dr. Roberts, 5th August 1893, the "horse-shoe" resemblance is almost obliterated.[5] Much greater prominence is given to the spindle-shaped axis originally noticed by Messier in

[1] *Astroph. Journ.* vol. ii. p. 162.
[2] *Phil. Trans.* vol. cxxiii. p. 461.
[3] *Cape Results*, p. 10.
[4] *Sidereal Messenger*, vol. iv. p. 38.
[5] *Celestial Photographs*, vol. i. p. 101.

1764. On the plate it is found to be encompassed by a dim envelope, uniting the various patches of nebulosity into a large oval, 18′ by 12′, to the north-western end of which an abortive "horse-shoe" is appended like an excrescence. A picture obtained under more favourable circumstances might bring these somewhat incongruous parts into an intelligible mutual dependence. Professor Holden collected evidence suggestive of variation in the Omega nebula,[1] but none that could be regarded as conclusive. "There has certainly not been any bodily shifting," Dr. Dreyer pronounced in 1887.[2] He was not, however, equally clear that partial fluctuations in brightness might not have taken place. The question remains an open one.

The spectrum of the Omega nebula was recorded as gaseous by Sir William Huggins in 1864. Nothing further is known about it.

Perhaps the most important of the nebulæ for purposes of comparative study is "30 Doradûs." Situated in the Greater Magellanic Cloud, the "looped" nebula may exercise, in Professor Pickering's opinion, a dominating influence over that extraordinary mixed assemblage. Yet it has the filmy and unsubstantial appearance of silver filagree torn in shreds and hung in the black sky. Its spectrum offers a remarkable combination of linear elements with strongly continuous radiance. Here, if anywhere, a frontier-instance between "white" and "green" nebulæ is to be found. Burton in 1874 affirmed the predominance in it of the fundamental nebular line; but the Harvard observers are less explicit. Professor Pickering briefly announced in 1892[3] the spectrum of this object to be "unlike that of other gaseous nebulæ"; adding in 1897[4] that its "constitution appears to be partly stellar and partly gaseous." Further, a sixth-magnitude star in Libra (A.G.C. 20,937) is said to reproduce the peculiarities of its mixed light, a discovery ranking among the most profoundly instructive of those made by Mrs. Fleming. Its full import may, however, develop only through prolonged investigation.

[1] *Amer. Journ. of Science*, vol. xi. p. 341, third series.
[2] *Monthly Notices*, vol. xlvii. p. 420. [3] *Forty-Seventh Annual Report*.
[4] *Harvard Annals*, vol. xxvi. p. 206.

Near the star ξ Persei on 3rd November 1885, Barnard discovered, at Nashville with a six-inch telescope, a "very faint, very large, diffused" nebula (N.G.C. 1499).[1] Six years later it came prominently into notice through a photograph taken at Halensee, near Berlin, by Dr. Archenhold.[2] The Willard lens was then repeatedly brought to bear upon it at Lick, and one of the resulting pictures, to which Barnard gave six hours' exposure 21st September 1895, is reproduced in Plate XXIX. The nebulosity extends over at least two degrees, and includes many "angular condensations." A round dark spot near the northern border strikes the eye at once. That it is "doubtless a hole in the nebula," Professor Barnard avers. But in a gaseous mass a "hole" could neither be produced nor maintained. Light in the perforated region must be suppressed unless it be intercepted, and the latter alternative involves consequences that may fairly be called inadmissible.

A drawing of the ξ Persei nebula, published by Dr. Scheiner in 1893,[3] embodies five photographic delineations obtained with a Voigtländer "euryscope" of four inches aperture, in times of exposure varying from one to six hours. He found it to be little inferior in size to the great Orion nebula, but totally different in plan of construction. It has strongly luminous borders, and these are connected by bright causeways crossing a comparatively obscure interior. There is no sign of a nucleus, nor any tendency towards the formation of one. Portrait-lenses, or some modification of them, seem to be the only kind of instrument with which impressions of this object can be secured; a plate exposed during six hours at the focus of the Potsdam thirteen-inch astrographic refractor showed no trace even of veiling from the prolonged impingement of its rays. They are equally ineffective, Dr. Archenhold states, upon orthochromatic plates—a fact reasonably held to imply that the nebula emits chiefly light-waves of short periods. In other words, it is a *green* nebula, and all but certainly gaseous.

A "vast and magnificent nebula" near Antares, seen imperfectly and fragmentarily, was disclosed in its entirety by Professor Barnard's photographic researches in 1895.[4] Its

[1] *Astroph. Journ.* vol. ii. p. 350. [2] *Astr. Nach.* No. 3082.
[3] *Ibid.* No. 3157. [4] *Ibid.* No. 3301; *Knowledge*, vol. xix. p. 205.

primary gathering-ground is about $\rho$ Ophiuchi, a quadruple star of fourth magnitude giving a helium spectrum; but $\sigma$, $\gamma^2$, and 22 Scorpii, besides other smaller stars, form subordinate foci. Antares itself is involved in the trailing skirts of this cosmic cloud, but may in reality lie far away from them. Furrowed by an intricate system of rifts, and pierced by obscure cavities, the Antares nebula is evidently in an agitated and unstable condition; and its marked tendency to cling to individual stars suggests that its development will take the direction of accentuating such local condensations. The example of the Pleiades was recalled to Professor Barnard; and it may be that the formation in Scorpio presents us with an analogous aggregation in an earlier stage of growth.

One in many respects similar was photographed in Cepheus by Professor Barnard 13th October 1893. He traced in it "numerous irregular vacancies and zigzag lanes," and noticed it to "mingle indefinitely with masses of small stars and become part of them."[1] This nebula is two degrees in diameter, and rudely circular in shape. Still more far-spreading and complex is a wonderful nebulous maze, vaguely centred at a point near $\xi$ Cygni, but extending outward to a distance of at least eight degrees. Dr. Max Wolf, who virtually discovered this vast formation by his photographs of 1891, considers it to embrace all the stars, bright and faint, that come within its scope;[2] and we cannot doubt that a heterogeneous system, partly stellar, partly nebular, is here presented to view. But the particularities of its composition evade for the present profitable inquiry.

Barnard's circular nebula in Monoceros (N.G.C. 2237), which to the eye seems to draw a line of circumvallation round the cluster within, but loses in photographs all trace of annularity, may provisionally be classed as "irregular." A fine picture taken by Dr. Roberts 5th March 1899[3] shows the nebulosity to extend over a space about 77′ by 67′, in the form of a cloudy aggregration "broken up into wisps, streamers, and curdling masses, densely dotted with stars," and including

[1] *Knowledge*, vol. xvii. p. 17.

[2] *Ibid.* vol. xiv. pp. 188, 230; *Observatory*, vol. xiv. p. 301; *Astr. Nach.* No. 3048.

[3] *Knowledge*, vol. xxii. p. 132.

PLATE XXIX.

E.

S.

N.

W.

Photograph of a Nebula in Perseus (N.G.C. 1499). By E. E. Barnard. Exposure, 6h.

"many dark areas with and without either stars or nebulosity. Some remarkable black tortuous rifts meander through the nebulosity on the north-preceding half of the nebula; their margins are sharp and well defined in the midst of dense nebulosity. They are as clearly cut as we see the cañons of great rivers, but their width may in reality be millions of miles."

Irregular, too, is a beautiful winged formation distantly resembling the Orion nebula, photographed by Schaeberle in the vicinity of Nova Aurigæ.[1] The physical investigation of all these objects will prove an arduous but interesting task. The measurement of their radial movements, especially, should help to define ideas regarding their true status in the heavens.

[1] *Astr. and Astrophysics*, vol. xi. p. 523; Wolf, *Astr. Nach.* No. 3130.

# CHAPTER XXXVIII.

## NONDESCRIPT NEBULÆ.

THE "dumb-bell" nebula in Vulpecula (M 27 = N.G.C. 6853) might almost be called a hybrid between the planetary and irregular species. Its affinities are indeed so numerous as to embarrass its classification. Imperfectly seen, it appears double, and such it was considered to be by the elder Herschel. What survives of it when the fainter parts are obliterated by dim air or bad definition, suggests the bell-shaped receptacles detached from the neck of an hour-glass. And, in fact, the succession of instances is unbroken, from bi-nuclear planetaries through the "dumb-bell" stage to unmistakable pairs of nebulæ thinly connected by hazy strips. This point has, however, been already referred to. The dumb-bell nebula, moreover, possesses a nuclear star, situated at the narrowest point of the neck; and it is difficult to conceive of the neck as other than a temporary arrangement. Many indications favour the idea that it will, sooner or later, break up and disappear, leaving the star regent over the masses finally disjoined. And it is curious to remember that just such an interjacent star occurs in several compound nebular systems.

A tendency to form a marginal ring is, on the other hand, visible in this nebula. A photograph taken by Mr. W. E. Wilson of Daramona, Ireland, which we are permitted by him to reproduce in Plate XXX., shows an incomplete bright border to be a leading feature in its construction. Whether in the future it is destined to become predominant, we can scarcely venture to surmise. The dumb-bell nebula is about 8′ in diameter. The bright framework can be seen in the photograph to be filled out into an elliptical shape by faint

S.

F.

P.

Photograph of the Dumb-Bell Nebula. By W. E. Wilson, F.R.S.
Exposure, $60^m$.

supplementary luminosity, which, however, is much stronger in the original negative. Dim protrusions at the ends of the major axis, traceable in Dr. Roberts's picture,[1] intimate opposite outflows, similar in cause and character to those suspected to proceed from the ring nebula in Lyra. The texture of the "dumb-bell" is lumpy and irregular. Presumably it is of an ellipsoidal form, and rotates on its transverse axis.

The spectrum is purely gaseous, and is dominated visually, with more than the usual emphasis, by the green nebulium line, while in the photographic region the ray at $\lambda$ 3727 was found by Von Gothard to be of quite peculiar strength.[2] Symptoms of helium-emission should be looked for.

Several objects have been described as miniatures of the Vulpecula dumb-bell, but the likeness may prove, on a more searching examination, to be only skin-deep. Among its supposed analogues are: (1) N.G.C. 1365, situated in Fornax, and described in Sir John Herschel's *Cape Results*.[3] It belongs, he says, to the class of "annular nebulæ with centres," but the ring breaks off, leaving the oval incomplete at its extremities, while the shorter axis terminates with two bright masses, between which lies a "resolvable" nucleus. (2) N.G.C. 5189. In Musca. A "general similitude" to the dumb-bell was noticed by J. Herschel.[4] (3) N.G.C. 3195. In Chameleon. A drawing is given in the *Cape Results*. (4) N.G.C. 1978. One of the nondescript inmates of the Magellanic Cloud. (5) N.G.C. 6905. A gaseous nebula in Cygnus, with a star in the centre, and four attendant upon it, like satellites. (6) N.G.C. 3226, 3227. A double nebula, near $\gamma$ Leonis, consisting of two hazy masses subsensibly united by a "neck," and enclosed in a dim, elliptical sheath. All these various structures may not, indeed, be traversing the same line of development. In some, the annular tendency will perhaps eventually prevail, in some the disruptive. The balance between opposing forces is unlikely to incline everywhere the same way, and upon its poise depends by supreme appointment the special form to be assumed in the course of ages by each individual system.

The "Crab" nebula in Taurus, discovered by Dr. Bevis in

[1] *Celestial Photographs*, vol. i. p. 113.

[2] *Astr. Nach.* No. 3738.

[3] *Cape Results*, p. 20.

[4] *Ibid.* p. 24.

1731, was again noted by Messier, 12th September 1758,[1] as a "whitish light, elongated like the flame of a taper." He took it at first for the comet he was in search of; and, to avert future confusion of the kind, adopted the memorable expedient of constructing a catalogue of nebulæ.[2] The specimen at present in question measures 5′ along its greatest diameter, and about 3′ across. Lord Rosse gave it its distinctive name from the protruding filaments resembling the claws of a crustacean, brought to view by his great reflector.[3] These have not yet been photographed. On a plate exposed during three hours by Dr. Roberts, 2nd February 1892, there came out an ovate body composed of "dense masses of clouds, with fainter areas between them," a deep bay on one side being counterbalanced by a projecting limb on the other.[4] No tentacular appendages were disclosed.

The spectrum of the Crab nebula appears to be rather more strongly continuous than is usual in the gaseous class, to which it unquestionably belongs. For at Harvard College in 1868 the green nebulium ray was recorded, and was suspected to have *less* refrangible companions.[5]

Another object of dubious relationships is Messier 77 (N.G.C. 1068), Lord Rosse's "blue spiral" in Cetus.[6] The description intimates an anomaly, since true spirals are "white," and give a continuous spectrum. Now the colour of this object corresponds, as might have been expected, to a gaseous constitution, whether of the normal kind or in certain ways peculiar, remains to be proved. Its form, too, is ambiguous. A drawing published by Lord Rosse portrays a round, faint disc more than 2′ in diameter, upon which are relieved the brighter coils of a definitely separated central mass. In Dr. Roberts's picture (see Plate XXVIII. Fig. 2), on the other hand, there is no trace of a convoluted structure. It shows "a stellar nucleus with projecting ansæ of dense nebulosity" surrounded by a faint zone, and that again "by a broad

[1] *Conn. des Temps pour 1784*, p. 229.

[2] Smyth, *Celestial Cycle*, p. 145 (ed. 1881).

[3] *Phil. Trans.* vols. cxxxiv. p. 322, cli. p. 715; *Trans. Royal Dublin Soc.* vol. ii. p. 47.

[4] *Celestial Photographs*, vol. i. p. 52.

[5] *Harvard Annals*, vol. xiii. pp. 64, 66.

[6] *Phil. Trans.* vol. cli. p. 713, plate xxv. fig. 6.

nebulous ring studded with strong condensations" like inchoate stars. A different aspect was, however, assumed by the object in a photograph taken by MM. Baillaud and Bourget in 1899 with the thirty-three-inch reflector of the Toulouse Observatory.[1] The nucleus here again resolved itself into the winding folds seen at Parsonstown, and a paler spiral formation served for its background. Its character continues in many respects enigmatical.

M 77 is copied, in Professor Holden's opinion, quite accurately by a nebula in the same constellation (N.G.C. 1084). Under the gaze of the camera it may resume the spiral shape obscurely visible to the Parsonstown observers, notwithstanding their final description of it as "a fine oval, with ragged edge and a mottled look," indented by "a dark bay north of the nucleus."[2] Judging by analogy, it should yield a gaseous spectrum; though the circumstance, considering its remoteness from the Milky Way, would be exceptional.

Messier 78 (N.G.C. 2068), in Orion, is a "singular wispy nebula," 6′ or 7′ across, enclosing a triple star, surmised to vary in light.[3] An arrangement of the more lucent nebulous tufts along a spiral curve, affirmed visually,[4] is denied photographically. Dr. Roberts's plate exhibits a central cumulus, sharply terminated on one side, vaguely diffused on the other, the dense nuclear part being surrounded by dim floccules with wide dark spaces between.[5] A smaller adjacent nebula (N.G.C. 2071) has a stellar focus, to which appurtenances like "mare's tails" are attached. The distance from centre to centre of the two nebulæ is about 15′ of arc, and they can be made out to be in faint nebulous connection; but neither, Dr. Roberts expressly states, gives indications of possessing a spiral form. Their spectra, which are probably discontinuous, have scarcely been examined.

That of "a fine, pale-white object"[6] in Canes Venatici is known to be continuous.[7] Discovered by Méchain in 1781,

[1] *Comptes Rendus*, t. cxxvi. p. 1191.

[2] *Phil. Trans.* vol. cli. p. 713; *Trans. Royal Dublin Society*, vol. ii. p. 32.

[3] Webb, *Celestial Objects*, vol. ii. p. 188 (5th edition).

[4] *Trans. Royal Dublin Society*, vol. ii. p. 51.

[5] *Knowledge*, vol. xviii. p. 253.

[6] Smyth, *Celestial Cycle*, p. 361.

[7] *Harvard Annals*, vol. xxxiii. p. 144.

M 94 (N.G.C. 4736) is large and bright;[1] its nucleus, which is granular in texture, and evidently globular in shape, being surrounded by a zone of extremely dim, and that again by a zone of relatively intense luminosity. The outer annulus appears, in a photograph taken by Dr. Roberts,[2] to be broken up into nearly a dozen irregular star-like condensations. Two abrupt opposite projections from it explain, possibly, the quasi-spiral aspect of the nebula in the Rosse reflector.

A circular object, one minute of arc in diameter, and of a "lucid pale-blue colour," was met with by the elder Herschel in the constellation Hercules, and ranged in the planetary class[3] (N.G.C. 6299). D'Arrest described it as a "nebulous disc," invested with a "nebulous sheath," so that its passing for a comet in 1819 is easily understood. Nevertheless, Sir William Huggins found it to shine with perfectly continuous light,[4] and it was thought at Parsonstown, on 9th May 1872, to be resolved into a globular cluster.[5] It should be added, however, that an undoubted planetary, N.G.C. 2022, was seen with the same instrument under a similar illusory aspect. There is indeed much difficulty in admitting the nebula in Hercules to be a genuine cluster. Its cometary envelope and the azure cast of its rays are almost contradictory of a stellar composition. But until a photograph of its spectrum has been obtained nothing can be definitely asserted on the subject. The quantity of light available for analysis is about equal to that given by a ninth-magnitude star.

A nebula in Virgo (N.G.C. 4900) looked, when ill-seen with the Rosse reflector, something like the Owl planetary in Ursa Major.[6] A bright patch in the centre seemed to have dark spots on either side, the whole being surrounded by a lucid annulus or coil. Yet on a plate exposed at Crowborough, during three hours, no spiral structure emerged to view, although the nebulous condensations visible in the interior were judged to be of the kind usually found to accompany spirality.[7] The

[1] J. Herschel, *Phil. Trans.* vol. cxxiii. p. 434; Rosse, *Trans. Royal Dublin Society*, vol. ii. p. 122.

[2] *Celestial Photographs*, vol. i. p. 81.

[3] Smyth, *Celestial Cycle*, p. 472; Webb, *Celestial Objects*, vol. ii. p. 137.

[4] *Phil. Trans.* vol. clvi. p. 390; *Harvard Annals*, vol. xxxiii. p. 144.

[5] *Trans. Royal Dublin Society*, vol. ii. p. 150.

[6] *Ibid.* p. 123.

[7] *Celestial Photographs*, vol. ii. p. 129.

formation, indeed, looks completely amorphous. It is probably of a non-gaseous nature.

The mutual relationships of many of the nebulæ just described are doubtless very close. Their elucidation offers a tempting and profitable field of research. Specimens in some respects anomalous are often the most instructive to study. Abortive features may be found in them, or half-developed characteristics, isolated from their accustomed surroundings, and thereby laid bare to scrutiny. Advantageous standpoints for comparison and correlation would thus be gained; and where these are effectively practicable, science cannot miss the path of progress.

## CHAPTER XXXIX.

### VARIABLE NEBULÆ.

THE occurrence of local changes of brightness is reasonably certain, as we have seen, in some of the great irregular nebulæ, and may be suspected in others. Variability affecting smaller objects in their entirety must then be admitted as possible. No doubt the phenomenon would introduce ideas difficult to adjust and unexpected; but the heavens are full of surprises. The immediate question to be put regarding it is, Does it really subsist? The answer must be given with extreme circumspection. The visibility of nebulæ depends upon contrast; the blackness of the sky has as much to do with it as the brightness of the filmy masses projected against it. They are besides apt to disappear with high magnification, and that for two reasons. First, because of the diffusion over a larger area of the same quantity of light; secondly, because of the restriction of the background in narrower fields of view. Hence there are drawbacks to the employment of large telescopes in nebular observation. The history of Tempel's Merope nebula, marked by vicissitudes ascribed again and again to intrinsic causes, now fully recognised as non-existent, is a warning against hasty conclusions on so delicate a point. The lesson has indeed been so thoroughly learned that changes of the sort have of late been announced only with a certain timidity, and under reserve. Caution in the matter can, indeed, hardly be blamed for exaggeration, in view of Swift's remark that, after the Krakatão eruption, many faint nebulæ absolutely disappeared.[1] Nor need we go beyond Chacornac's "temporary nebula" for an exemplification of optical caprices. On 19th October 1855

[1] *Sidereal Messenger*, vol. iv. p. 4.

the French observer noticed a striated haze (N.G.C. 1988) attached to the star ζ Tauri, which seemed to have gained brightness in the ensuing January. No one else, however, saw it, and it had vanished by 20th November 1862. According to Tempel it never shone in the sky, but was a telescopic creation—a false image of an eleventh-magnitude star near ζ Tauri;[1] and Burnham unhesitatingly adopts this opinion.[2] Thirty years later its reality could have been tested by photographic means; but astronomers in those days had to rely upon the fallible human retina.

Chacornac's phantom formation emerged near the site of two genuine nebular Novæ. On 11th October 1852, Hind detected, close to a star, then of the tenth magnitude, but since registered as an irregular variable under the designation T Tauri, a dim, round nebula (N.G.C. 1555) which brightened steadily until 1856, when it was obvious to general observation. A comparatively rapid decline ensued. Auwers[3] could barely discern the object with the Königsberg heliometer in January 1858; to d'Arrest,[4] using the eleven-inch Copenhagen refractor, it was wholly invisible 3rd October 1861; in 1862 it was vainly sought at Paris and at Malta with Foucault's and Lassell's great mirrors; Hind himself was unable to find it; Secchi, under the pure Roman sky, was equally unsuccessful; only at Pulkowa it continued to glimmer just perceptibly for a few months longer. From 1863 the sky in its place seemed a dead blank. At last, 15th October 1890, Mr. Burnham requested his colleague, Professor Barnard, to examine the region with the Lick thirty-six-inch, whereupon a nebulosity about 50″ in diameter, and so faint as to be at the limit of vision, was detected[5] (see Fig. 49). Burnham too saw it, but believed that he could not have done so independently, his splendid powers of sight being better adapted to the discernment of concentrated than of diffused light-rays.

The nebula was again observed by Barnard—and with somewhat increased facility—in February 1895.[6] Seven

[1] Dreyer, *Memoirs Royal Astr. Society*, vol. xlix. p. 215.
[2] *Monthly Notices*, vol. lii. p. 455.
[3] *Astr. Nach.* No. 1391.
[4] *Ibid.* No. 1366.
[5] *Lick Publications*, vol. ii. p. 176.
[6] *Monthly Notices*, vol. lvi. p. 66.

months later he was amazed to find it utterly gone! His search was repeated on three nights, under supremely good conditions, with the same negative result. And the object, so far from evading the grasp of large apertures, is peculiarly fitted for observation with them, owing to its small size and compact shape. Nevertheless, the forty-inch Yerkes refractor failed to show it at all in 1897, and barely enabled Barnard to catch a glimpse of it, 28th September 1898.[1] Finally, Professor Keeler obtained faint images of it on two Crossley plates, exposed during four hours each, in December 1899.[2] A copy of his drawing from them is given in Fig. 50. It exhibits the nebula as composed of three vaguely defined patches, united by a dim haze, the camera having, as usual, descried structural complexities inappreciable by the eye. On 20th January 1900, the great refractor just availed to bring it into view, and it has not since been heard of. To Professor Keeler it appeared inconceivable that in its present obscure state it could ever have been seen with small telescopes; and indeed the evidence of variability is conclusive. Will it ever recover any of its lost brightness? It may be doubted. The changes so far undergone by it have been, though comparatively slow, strictly analogous in character to those of "new" stars; a presumption hence arises that it will share their fate of permanent extinction. There is much reason to suppose that Hind noted in 1852 an early stage of its kindling; that its maximum in 1855-56 was solitary, its declension irretrievable.

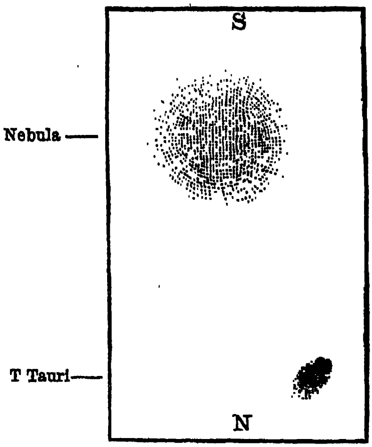


FIG. 49.—Sketch of T Tauri and Hind's Nebula, 15th October 1890 (Barnard).

Strange to say, the phenomenon was duplicated. While looking fruitlessly for Hind's nebula, Otto Struve came upon another unfamiliar object (N.G.C. 1554) 4′ east of its pre-

[1] *Monthly Notices*, vol. lix. p. 372. [2] *Ibid.* vol. lx. p. 424.

decessor's empty place. This was early in 1868; and the Nova—for d'Arrest was sure of its previous non-existence[1]—was kept in view until 1877, when absolute obliteration covered it. Even Barnard's quest for it in 1890, 1895, and 1899 was ineffectual. Its former position is marked in Keeler's drawing (Fig. 50) by the thirteenth-magnitude star *b*, but no

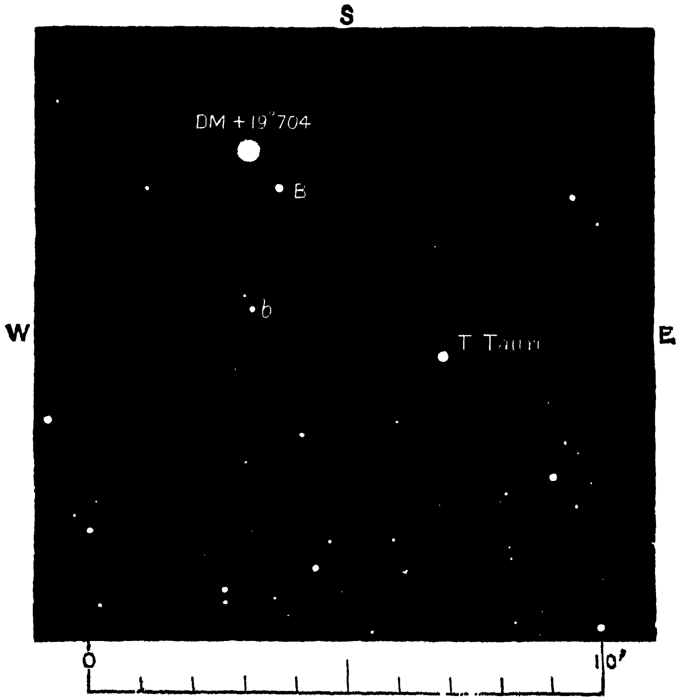



FIG. 50.—Region of T Tauri and Hind's Variable Nebula. Drawn from Photographs by Professor Keeler.

nebulous impression was there made upon the plates. Dr. Roberts had indeed already, in 1890,[2] vouched for its photographic disappearance. When last seen by Tempel,[3] 8th November 1877, the nebula was 90″ across, and d'Arrest had expressly recorded the presence in it of an eccentrically situated, though definite nucleus.

[1] *Astr. Nach.* No. 1689; Barnard, *Monthly Notices*, vol. lv. p. 442.
[2] *Monthly Notices*, vol. l. p. 440.
[3] *Astr. Nach.* No. 2212.

Hind's and Struve's nebulæ were bright enough, as Professor Barnard recalled wonderingly,[1] to be ranked, soon after the middle of the last century, in Herschel's first and second classes respectively. Both were watched "and measured by the best observers then living," and "were easily visible in ordinary telescopes." Yet one survives only as a fitful shimmer; the other is utterly, and probably for ever, quenched. They are perhaps obscurely connected, and the system—if such it can be termed—may include the nebulous variable T Tauri; although nebulæ and star alike seem to fluctuate in complete independence one of the others.

These are the only authentic instances of temporary nebular developments; but allegations of nebular light-change are common. Some have proved groundless; not a few, however, rest on a solid substratum of fact. The following may serve as specimens.

On 17th October 1785 William Herschel discovered, not far from Algol, "a pretty bright star with two faint branches" (N.G.C. 1186). Sir John verified the observation, while estimating the star at only fourteenth magnitude (about twelfth on the modern scale). Yet neither it nor its appendages could be seen with the Parsonstown reflector, and d'Arrest, after diligent and repeated search, affirmed decisively, *Nostra ætate in hac regione tale quid non exstat in cælo.*[2] The lost object, nevertheless, came again into view in 1891. On 31st January and 26th February of that year, Bigourdan, using the thirteen-inch Paris equatorial, perceived it as a twelfth-magnitude star, with an unmistakable "fan" of nebulosity spreading from it over 1′ of arc. Only a fortnight later, Spitaler made a drawing of the object with the Vienna twenty-seven-inch, and described it as an elongated nebula, not regular enough to be called elliptical, 2′ in extent, and including a focal star of the eleventh magnitude.[3] And Burnham, in the following August, "readily found in the proper place a *tenth*-magnitude star involved in a faint elongated nebula" measuring at least 2′ or 3′.[4] During the course of 1891, accordingly, the star seems to have

[1] *Monthly Notices*, vol. lv. p. 451.
[2] Quoted by Bigourdan, *Comptes Rendus*, t. cxii. p. 471.
[3] *Astr. Nach.* Nos. 3030, 3167, 3168.
[4] *Publications of the Lick Observatory*, vol. ii. p. 172.

been progressively gaining light and the nebula compass. But if the star only were variable, the attached nebula would have appeared to shrink and become effaced as the bright point within it acquired intensity. Its simultaneous increase could not have been counterfeited. Proof was afforded by it that the growth, like the previous failures of luminosity, were due to influences diffused throughout every part of the formation.

The next variable nebula was a "find" of Barnard's. It was conspicuous to him 30th November 1888. He judged it equal to a ninth or tenth-magnitude star, and remained convinced that its lucidity was of recent origin. Three years later it had parted with quite four-fifths of its lustre, and had faded down nearly to evanescence.[1] It is situated in Cetus. No information is at hand as to whether its decline has continued since 1891. Unless arrested, it must, before the century closed, have carried it out of sight even of the chemical retina, and the object should then probably be relegated to the class of "temporaries." The question is of great interest, and might be answered by taking one long-exposed photograph with a portrait-lens or a large reflector.

This is not the only case in which an accession of brightness has been thought to be demonstrated by the lateness of discovery. A nebula was encountered by Tuttle in Draco, 1st September 1859 (N.G.C. 6643), which, in d'Arrest's opinion, should certainly have been caught in the meshes of the Herschelian nets unless in their time comparative obscurity had enveloped it. Similarly, a nebula in Camelopardalis detected by Barnard in 1889,[2] and again independently by Denning in 1890,[3] could not long, Barnard considered, have been thus readily apparent. He recommended its being kept under surveillance as a probable variable, but as yet it has shown no sign of being so;[4] unless, indeed, Swift's earlier observation of the same object, recorded without date by a simple entry on a star-map,[5] indicated a previous maximum. Another instance of a possible rise in the scale of luminosity is afforded by a small, fairly bright nebula in the Camelopard, first

[1] *Astr. Nach.* No. 3097; *Monthly Notices*, vol. lv. p. 452.
[2] *Astr. Nach.* No. 3097. [3] *Observatory*, vol. xv. p. 104.
[4] Denning, *Astr. Nach.* No. 3111.
[5] *Astr. and Astrophysics*, vol. xi. p. 566.

observed by Denning 30th September 1891, and casually again four times in the ensuing month. Yet his many previous reviews of the sky-contents in that neighbourhood had failed to elicit any trace of its existence. Like Barnard's and Tuttle's "new" nebulæ, however, it has apparently come to stay; and since variability is in sidereal bodies usually an ineradicable property, the hypothesis of an ascent from invisibility cannot safely be accepted until a corresponding descent has been entered upon.

The irregular variability, on the other hand, of two nebulæ adverted to by Winnecke in 1877-78[1] is almost incontestable. The first (N.G.C. 3666) is in Leo. Elliptic in shape, in size 90″ by 40″, it was marked "very bright" by the elder Herschel 15th March 1785, but "extremely faint," 23rd March 1830, by the younger, who added the comment, "This nebula must have changed greatly if ever it belonged really to the first class." But its waning was not definitive. Boguslawski inscribed it as a *bright object* in 1840 on the Berlin Academy star-map of that region; and Winnecke found it, 10th April 1878, of unquestionable primary rank. Yet meantime, in 1863, d'Arrest had described it as *subobscura*, and manifestly of third-class lustre; while again, on 24th May 1887, Dr. Dreyer perceived its diminished radiance only with the utmost difficulty. Its further history remains untold.

Winnecke's second variable (N.G.C. 955) is an inmate of the crowded nebular district in Cetus. It consists, Burnham says,[2] of long, narrow "nebulous wings on either side of a bright central condensation." "On the whole," he continues, "it is rather a curious object, and should be easily found and seen." This was in 1891, and agrees quite well with Dreyer's notice of the object in November 1887 as "fully of the second class."[3] The case for change rests upon its invisibility to Schönfeld in December 1861, and to Vogel in November 1865; although in 1856, 1863, and 1868 it had been seen at a glance by Schönfeld himself, no less than by d'Arrest and Winnecke.

[1] *Monthly Notices*, vol. xxxviii. p. 104; *Astr. Nach.* No. 2293; *V. J. S. Astr. Ges.* Jahrgang xiv. p. 167.

[2] *Publ. Lick Observatory*, vol. ii. p. 172.

[3] *Memoirs Royal Astr. Society*, vol. xlix. p. 213.

Winnecke's nebulæ were at first held by him to be periodical; but this they certainly are not. No fixed relation to time has so far been shown to govern nebular fluctuations. They either consist—according to the best evidence at command—of a solitary maximum, analogous to the outburst of a new star, or of irregular accessions and losses of light. No case of cyclical recurrence is on record. Photography is clearly destined to play an important part in the investigation of this difficult subject; its aid will be peculiarly welcome where visual faculties are often baffled, embarrassed, and deceived.

Nebular variability is indeed a phenomenon not only evasive to the senses, but startling to thought. It cannot be even remotely assimilated to the light-changes that progress in certain globular clusters; it is independent of geometrical conditions, of orbital movements, of planes and periods. Its cause defies conjecture; we can only be sure that it acts upon a prodigious scale. Thus Hind's nebula in Taurus measured at least 2′ across. Its parallax was almost certainly less than one-tenth, and may not have exceeded one-hundredth of a second. The larger value would give, for the smallest admissible linear diameter of the object, 1200 astronomical units (radii of the earth's orbit) or 111,000 million miles. Centred on the sun, it would extend on every side to twenty times the distance of Neptune, the equation of light within the vast formation being six and a half hours. Yet it kindled as a whole, through the pervading influence of some far-reaching event. Did another dark nebula sweep through it? We dare not pronounce. Its mysterious brightening, however, hints at the existence of an indefinite multitude of similar bodies lurking in the obscurity from which, by some rare chance, it emerged. It introduces us, in fact, to a realm of invisible nebulæ, impenetrable by observation, and hence pre-eminently adapted for the sports of scientific fancy.

Hind's and Struve's vanished nebulæ were presumably of gaseous composition, like the adjacent glow round T Tauri;[1] Winnecke's variable pair doubtless shine with the white light characteristic of the elliptic family to which they structurally

[1] *Publ. Lick Observatory*, vol. ii. p. 176.

belong. Their remoteness from the Milky Way points to the same conclusion. Luminous instability does not then appear to be associated in nebulæ with any special radiative quality. Those giving continuous, and those giving discontinuous spectra may equally be affected by it.

# CHAPTER XL.

## THE NATURE OF NEBULÆ.

THE relations of white to green nebulæ are obscure. Unitive links between the two classes have yet to be established. In most respects they stand at present widely apart. They present a superficial likeness, but their dissimilarities seem to be radical. They are unconnected by any marked spectral affinities; they differ organically in structure; their distribution on the sphere is regulated by opposite principles. Hence their genealogical precedence remains unsettled. It would be rash to say that either family developed from the other, or even that they are collateral offshoots from a common stock. That a line of continuity will, sooner or later, become traceable is more than likely, but we must wait for the guidance of facts with regard to it; premature divinatory efforts are usually good for less than nothing.

As to the constitution of white nebulæ, we seem on the verge of knowing something definite. Premonitions of their being a species of fine-grained star-cluster have become audible. The subject, however, is not ripe for discussion. A comparatively advanced stage has, on the other hand, been reached by the problems connected with gaseous nebulæ, since their spectra let us, to a certain extent, into the secret of their composition. This, on the whole, seems to be remarkably uniform. Individual differences, it is true, both physical and chemical, distinguish the various members of the class; but they are of a subordinate kind. We may then safely attempt to generalise as regards a few of their more obvious properties. Three of these can be at once enumerated:—

(1) Gaseous nebulæ are almost perfectly transparent.[1]

(2) They shine with extreme feebleness.

(3) Their mass is vanishingly small in proportion to their bulk.

We will take each point separately. That nebulæ offer no appreciable obstacle to the transmission of light is attested by the unaltered radiance of stars shining through them. No absorption that can possibly be due to the cosmic fog in which they are plunged to depths of many millions of miles, is traceable in the spectra of such objects as $\theta$ Orionis, of $\rho$ Ophiuchi, of Maia or Merope in the Pleiades. Similarly, the central stars of planetary nebulæ shine through an interposed medium, the extent of which is measured by the radius of each gaseous globe; and this, by a rough minimum estimate, can rarely be less, and must often be a great deal more than 50,000 to 60,000 million miles. Yet from the heart of these extraordinary formations the light of their nuclei comes to us, so far as it is possible to judge, absolutely intact. The impotence of comets for light-stoppage is thus vastly enhanced in nebulæ.

The feebleness of their luminosity is a matter of direct observation. A shining superficies, unlike a shining point, loses none of its lustre with increased distance. Its area of course diminishes according to the law of inverse squares, but every minute element of that area continues to radiate with the same intensity as before. The sun, for instance, is no less *bright* as viewed from Neptune than when it crosses the meridian of Khartoum, but it is 900 times *smaller*. So with the nebulæ. They are really as faint as they appear. Using the best available data, Mr. Ranyard arrived at the conclusion that a planetary of the most vivid kind emits per square mile less than $\frac{1}{22,000}$ millionth of the light sent abroad by the solar photosphere. This implies—adopting the result of Langley's experiment at Pittsburg—that white-hot iron glows at least 4,000,000 times more powerfully than the bluish disc of the "Saturn" or the "Owl" nebula. Moreover, the differences in areal lustre between one nebula and another represent actual varieties of emissive strength. Remoteness has nothing to do with producing them. A *debilissima*—a "breath-stain"

[1] Ranyard, *Knowledge*, vol. xv. p. 132.

on the sky—may be as near to us as the great hiatus in the vault through which Huygens half-imagined the blazing of empyrean fires.

Finally, nebulæ being prodigiously voluminous and of apparently insignificant mass, must be of exceedingly low mean density. This fundamental fact was realised with uncompromising distinctness by Mr. Ranyard in 1892.[1] Taking, for illustrative purposes, the Orion nebula to be a sphere 20′ in diameter, composed uniformly of materials 1,000,000 times rarer than atmospheric air at sea-level, he found that its mass would be such as to impart, to a body at a distance from its centre equal to that of $\alpha$ Centauri from ourselves, a circular velocity of 180, or a parabolic velocity of 255 miles per second. In the neighbourhood of the nebula, accordingly, there should be a marked prevalence of large proper motions. A star, travelling across the line of sight under the influence of its attraction at the rate of 100 miles a second, would, it was shown, have an annual displacement on the sphere of no less than 25·5″, and this independently of remoteness. For with the same angular dimensions, the solid contents of the nebula would increase as the cube of the distance assumed for it; while the seeming velocities of bodies in gravitational dependence upon it would undergo no change. This is rendered obvious by a moment's consideration. For take any given star circulating round its centre of gravity at the rate, let us suppose, of 100 miles a second. And let us further suppose, to begin with, that the distance of the system is such that light would spend ten years on the journey thence to our eyes. Let us now double that distance and follow out the consequences. First, the nebula is eight times more massive than would have comported with the previous arrangement. Next, the revolving star is twice as far from it as before, since the apparent interval has not changed. Whence we easily gather, by the application of Kepler's third law, that it now moves with double its previous speed. But its distance has, by hypothesis, also been doubled; consequently, its proper, or apparent motion remains just what it was. If, then, the stars about the Orion nebula were really in swift circulation, they should appear to be conspicuously progressive. This, however, is so far from being

[1] *Knowledge*, vol. xv. p. 191.

the case that the region is one of exceptional fixedness. The spectroscopic information at command is to a corresponding effect. The six brightest stars of the constellation, measured at Potsdam in 1892, proved to be all affected, in varying degrees, by the retreat of our system from that locality of the heavens, but gave no signs of travelling rapidly on their own account. The conclusion is inevitable that the Orion nebula —and it may be accepted as typical—contains inestimably less matter than should be comprised by it if its average density were that of a Crookes vacuum. Mr. Ranyard, indeed, assigned to it a consistence not exceeding $\frac{1}{10,000}$ millionth that of air at standard pressure, which, he continued, "would about correspond to the mean density of the solar nebulous mass, supposing it to have been spherical when its radius was a little more than 107 astronomical units, or when the sun occupied a sphere with a radius of a little more than three and a half times the distance of Neptune." The potential solar system in those days lay muffled in the haze of a small planetary nebula.

Yet it is impossible to conceive of nebulæ as formed simply of matter in an aerial condition. They are no mere vague effusions. They possess definite and characteristic structure. Lord Rosse,[1] indeed, thought sharpness of contours distinctive of the gaseous kind. Mr. Maunder [2] speaks of their "strange and complicate shapes, showing here and there strongly-marked outlines"; and he adverts to the difficulty of explaining this peculiarity in vast, uncontrolled extensions of rarefied gas. The abolition of this incongruity was one of the strong points of Sir Norman Lockyer's "meteoritic hypothesis" of nebular constitution. The spectroscope, it is true, pronounced against it; nebular chemistry has very little in common with the chemistry of "uranoliths"; yet amid much that was precarious or unsound, the valuable idea was introduced that a proportion of solid matter must enter into the composition of nebulæ. Its condition and distribution, however, remain unknown. It would seem to be devoid of light, for the faint continuous spectrum accompanying the nebular bright lines would be displayed even by a homogeneous gaseous mass, unless its radiations were of purely superficial

[1] *Phil. Trans.* vol. clviii. p. 72.

[2] *Knowledge*, vol. xix. p. 39.

origin.[1] But here we meet the unresolved enigma of nebular luminosity. How do they shine? Is it through the direct agency of heat? Experimental evidence does not countenance this view. In the laboratory, hydrogen and helium can be induced to give out their characteristic rays only under the stress of electrical excitement. The concomitant high temperature might—as Sir William Huggins pointed out in 1891 [2]—prevail only along the path of the discharge, while the surrounding gases remained cool, producing inequalities in heat-distribution similar to those believed to exist in vacuum tubes. If, on the other hand, nebular emissions were of simply thermal production, the whole radiating mass should be at nearly the same pitch of incandescence; for if the temperature were lower in some than in other of its parts, absorption lines or reversals would betray the fact, and the nebular spectrum bears no legible marks of selective light-stoppage. Yet it is eminently improbable that formations so circumstanced are, in their entirety, excessively hot. Their solid inclusions should, if they were, glow powerfully, and strong continuous radiance would replace the dim band, grey through faintness, actually seen. On the supposition, however, that electrical discharges cause the glow of nebulæ, their average temperature, judging by Dr. Scheiner's experimental results, might approximate to absolute zero.

The word "temperature," indeed, when applied to matter in the last stage of attenuation, has an extremely dubious meaning. Taking the kinetic theory of gases to represent the literal truth, we find the effects of heating upon them to be twofold, namely, increase (1) of translatory, (2) of internal energy, the latter being perhaps a consequence of the former. Since, then, their constituent particles travel faster when heat is applied, they come into mutual collision more frequently and more violently. That is to say, if their number per unit volume remains the same. Let, however, the density of the gas be reduced, other things being unchanged, what will ensue? There will be fewer encounters in equal times, but they will *not* be less violent, since the mean rate of the molecules has undergone no alteration. Hence, apart from one qualifying circumstance,

[1] Clerk Maxwell, *Theory of Heat*, 10th ed. p. 245.

[2] *Cardiff Address*, p. 21.

the same species of vibration should be set going as when the gas was denser and equally hot. The qualifying circumstance is this. During the lengthened intervals between the collisions, the molecules are radiating — that is, imparting energy to the ether. If their free paths were sufficiently protracted, they would—if that be possible—lose all they possess, and need to be fully restocked at each encounter. The comparative isolation of the molecules would accordingly result in their being mostly dark, and what we must call *cold;* so that the extreme subtlety of matter seems incompatible with a high temperature in any intelligible sense of the term. But there is more. Reduction of pressure would have for its immediate result a general diminution of luminosity. In all probability, it would also produce a selective effect, for if, as seems likely, certain modes of molecular vibration are more persistent than others, they would, with the progress of cooling after each impact, tend to predominate, and the balance of intensity among the spectral lines of a glowing gas would thus be sensibly altered. Here, then, an explanation might be sought of the spectral anomalies of hydrogen in nebulæ. Nevertheless, it does not run quite smoothly, since up to the limit of possible rarefaction in vacuum tubes the crimson line of hydrogen gains consistently in strength.[1] A corresponding difficulty presents itself in connection with the helium spectrum.[2] "Green tubes" are at a higher degree of exhaustion than "yellow." Yet in nebulæ the green ray is invisible; nebular helium radiates only $D_3$ with a few members of the same "set." By means of artificial exhaustion, accordingly, the nebular spectrum cannot apparently be imitated. The only experimental clue to its origin, in fact, is in Professor J. J. Thomson's observation (already mentioned) that F and C are of interchangeable intensity at the negative and positive poles of a hydrogen tube.

To recapitulate. Two fundamental problems regarding gaseous nebulæ press for solution—one connected with their structural forms, the other with the nature of their light.

[1] E. S. Ferry, *Physical Review*, vol. vii. p. 6; Lewis, *Astroph. Journ.* vol. x. p. 141.

[2] Maunder, *Knowledge*, vol. xix. p. 286.

Do they continuously fill the spaces they appear to occupy, or should we figure them to ourselves as collections of discrete bodies comparatively wide apart? In the former case the dark gaps and chasms which form one of their leading features should be ascribed, not to the absence of matter, but to defect of shining power, illuminative, not architectural contours being disclosed by them. In the latter, chiaroscuro effects would be reliable indices to the distribution of material.

Secondly, we are confronted with the mystery of their shining. Why and how are they lucent? Are they bright as a consequence of thermal or electrical stimulation, or is their radiance some undefined species of luminescence or phosphorescence? The answer must be given in view of the three following peculiarities of their spectra: (1) The leading hydrogen line in them is F, not C. (2) Helium shines in them as if in a "yellow" tube. (3) Reversals are absent; lines of absorption make no assured appearance, either as superimposed upon, or as subjacent to lines of emission. None of these points are easy to decide. Their consideration involves doubts and queries of an abstruse nature; but it will not therefore be neglected. Indeed, such a region of inquiry as is here presented, where we feel that at every step the Unknown may merge into the Unknowable, has a particular and an illimitable fascination.

# CHAPTER XLI.

## THE PHYSICS OF THE MILKY WAY.

THE Milky Way is an integral part of the great sidereal system. It marks the equatorial girdle of a sphere containing stars and nebulæ variously scattered and aggregated. The whole material creation is, to our apprehension, enclosed within this sphere. We know nothing of what may lie beyond. Thought may wander into the void, but observation cannot follow. And where its faithful escort halts, positive science comes to a standstill. Fully recognising the illimitable possibilities of Omnipotence, we have no choice but to confine our researches within the bounds of the visible world. That it *has* bounds is evident from the consideration that it possesses shape and parts. Indefinitely extended, star-filled space could have neither. Hence it offers to the human mind an intelligible problem—a problem perhaps too intricate for definitive solution, yet coming well within range of attack. The siege operations may be protracted through many a campaign; but in conducting them we shall climb from peak to peak of the Alpine chain of truth, and gain continually wider views of the majestic scene that encompasses and enchants us.

The structural relations of the cosmos may evidently be looked at from many sides; our immediate concern is with but one of its aspects. We have only to consider the nature of the materials used for the building of the edifice and the plan of their apportionment to its different sections. These materials consist of gaseous and white nebulæ in all their varieties; of star clusters, globular and irregular, and of the sundry species of stars; and even a cursory inspection shows that they are not piled together at random. Each class, on

the contrary, obeys its own law of distribution; and the distribution of sidereal, as of animal species, is the outcome of their history, a test of their longevity, an index to their nature. They are *where* they are, because they are *what* they are.

There seemed, twenty years ago, very little reason to anticipate that the photographic method could ever be used to advantage for investigating the physics of the Milky Way; yet it has, especially in Professor Barnard's hands, proved most effective in that difficult branch of inquiry. The requisites were peculiar. The galactic drifts are made up of very small stars—usually of fourteenth to sixteenth magnitude, or even fainter,—and the sensitive plate perceives them, not, as the human eye does, collectively, merged into a nebulous surface, but one by one as light-points. Hence their rays need to be powerfully concentrated in order to make any chemical effect with a moderately long exposure. Moreover, the field must be large enough to show the colossal forms into which these stellar units are grouped. For each picture a canvas of at least 100 square degrees must be available. Hence telescopes of the ordinary type, however powerful, are, for this purpose, entirely useless. An ordinary village photographer's apparatus would be better adapted to it. Professor Barnard obtained his remarkable series of delineations with the "Willard lens," a doublet of six inches aperture and thirty-one focal length, constructed at New York in 1859.[1] They extend over a large part of the Milky Way, but leave lacunæ, the filling up of which should be the diploma-performance of the new Bruce lens. It might indeed be supposed that a few specimen sky-scapes in galactic regions would suffice to afford practical acquaintance with the entire round; but this is very far from being the case. No feature of the Milky Way is more surprising than its inexhaustible variety. No "law of condensation," such as prevails in globular clusters, is there traceable. Each section follows its own method of aggregation. In one, cloud-forms are met with of the cirrus type; in another, they recall breaking waves or tossing spray;[2] again, groups of irregular bright spots alternate with extensive

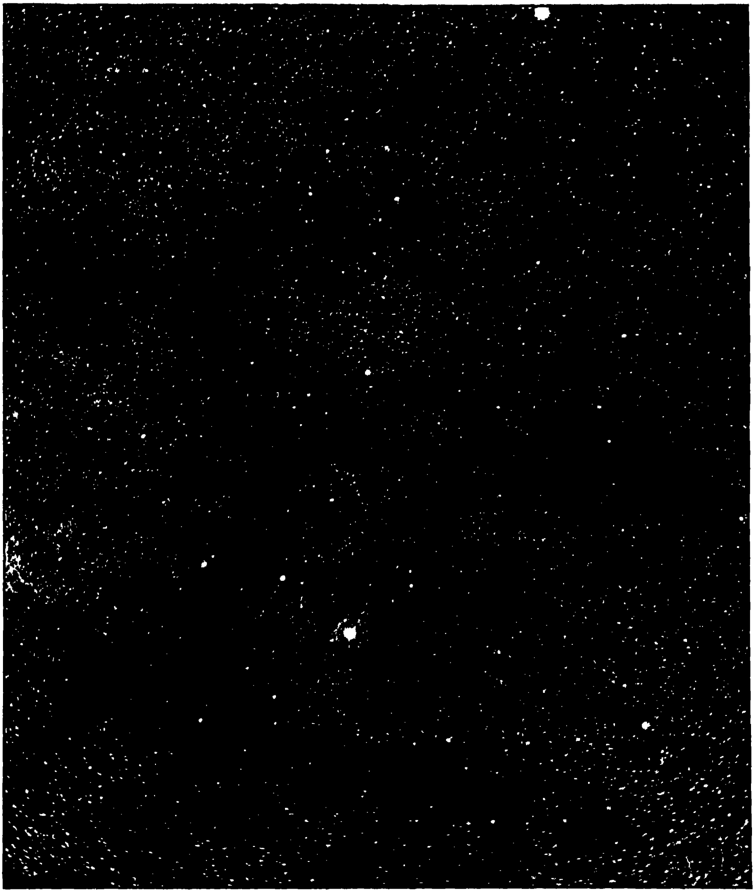
[1] Barnard, *Monthly Notices*, vol. l. p. 310.
[2] *Ibid.* p. 314; *Astr. and Astrophysics*, vol. xiii. p. 179.

ramifications and rifts; here the starry fabric is coarse-grained, there of microscopic fineness; while for heterogeneous scattering in many quarters, there is substituted in others an apparently designed arrangement of the stars into rings, chains, and ellipses.

Barnard's photograph in Ophiuchus, reproduced in Plate XXXI., has characteristics demanding earnest attention. The bright star below the middle of the plate encircled by a halation ring is $\theta$ Ophiuchi, an object spectrally akin to Bellatrix, radiantly white and marked by helium absorption. A "long, dull vacancy," visible to the naked eye, stretching east and west below (south of) Theta, comes out as "an irregular rift in the sheeting of stars," of highly complex relations. It circuits the east as well as the north and south sides of the bright mass in which the star is placed, breaks up to the north into scattered dark openings, and straggles on to the western edge of the plate, whence—as other photographs of the series show—it communicates with some of "the great vaçant lanes" in the "wonderful nebulous region about $\rho$ Ophiuchi.[1] The most singular feature, however, of the galactic chasms visible in our figure is the presence in them of two gradations of obscurity. Darker details can be made out on the dark background, recalling the analogy (which did not escape Professor Barnard's notice) of the "black holes" in the umbræ of active sun-spots. The conviction was thus, he added, almost enforced that the Milky Way rests here upon a far-reaching stratum of nebulous, or quasi-nebulous matter.

The reality, the frequency, and the determinateness of the black openings in the Milky Way, dimly seen with the naked eye, constitute one of the most important facts regarding the nature of that formation attested by the camera. It is true that their great exemplar in the southern heavens—the "Coal-sack" in Crux—seemed, in a photograph taken by Dr. Russell of Sydney, 13th August 1890, to be embroidered with small stars over three-fourths of its area;[2] but this is an unessential trait of the phenomenon. The fundamental circumstance connected with it is the extensive and complete perforation of the dense galactic stratum lying behind the starry network; and

[1] *Astroph. Journ.* vol. ix. p. 157.
[2] Ranyard, *Knowledge*, vol. xiv. p. 112.



Photograph of the Milky Way in Ophiuchus (Barnard).

of this stratum there is no trace in the Sydney picture. Only the foreground of the scene is delineated in it; the backward stretching ranges remained inaccessible with the means employed. The true Coalsack, then, has not yet been photographed, and we are ignorant of the precise form which it will take upon the sensitive plate. The exposures made at Lick, however, effectively reached the piles of luminous dust which form the ultimate reality of the Milky Way, and brought into view with insistent clearness the pits and furrows of almost absolute darkness by which they are frequently interrupted. One is perpetually reminded, in looking at these autographic records, of Herschel's exclamation of amazement when his telescope plunged suddenly into an unfathomable abyss in Scorpio: *Da ist wahrhaftig ein Loch im Himmel!*

Now "holes" of the kind have a very wide cosmical significance. The great rift, by which the entire galactic structure is divided throughout one-third of its circumference, is only a magnification of innumerable cracks and fissures yawning amid its component star-masses. And the dark lanes in globular clusters are plainly of kindred origin. Moreover, the riddled aspect of the Milky Way in certain of its sections is continually reproduced both in nebulæ and clusters—in nebulæ, whether gaseous or stellar, as well as in diverse species of clusters. The fact is a general one, that in all the forests of the universe there are glades and clearings. How they come to be thus diversified we cannot pretend to say; but we *can* see that the peculiarity is structural—that it is an outcome of the fundamental laws governing the distribution of cosmic matter. Hence the futility of trying to explain it as of incidental origin, as a consequence, for instance, of the stoppage of light by the interposition of obscure bodies, or aggregations of bodies, invisibly thronging space. That dark stars exist, singly and in systems, and dark nebulæ no less, we have been almost inevitably led to conclude; but the galactic clefts cannot be reckoned among their manifestations. They are, on the contrary, what they appear to be, intervals of starless space between neighbouring star-clouds, and suggest processes of disintegration[1] advancing with inconceivable slowness towards unimagined issues. These wonderful collections

[1] Barnard, *Report Harvard Conference*, Aug. 1898, p. 19.

are then in a state of flux; they are passing from one condition to another; Supreme Power is at work in dispersing or re-fashioning them, sending abroad their aggregated suns like flying sparks from the anvil.

But are those sparks indeed suns on the scale of our own? The answer to be given depends upon our estimate of their average distance. They are undoubtedly very remote. It may be taken as certain that they lie beyond the sphere occupied by the Durchmusterung stars—that is, by the ordinarily distributed stars of our system down to 9·5 magnitude. How much farther beyond, we are, however, unable to say. The thronging orbs of the Galaxy are by no means of uniform brightness. A recent inquirer [1] concludes that they range from the sixth to the sixteenth magnitude; and the statement, which probably falls short of the truth, implies that stars enormously disparate in apparent lustre are at sensibly the same distance from ourselves; hence, that the crowd of small or medium-sized bodies collected in the Milky Way are dominated by veritable giants, more sparingly distributed. Professor Barnard endeavours to bring this state of things into conformity with received standards by levelling down the dimensions of galactic constituents.[2] To the ruck of them he assigns scarcely more than planetary rank, so as to escape the necessity of admitting fabulous magnitudes for their leaders. But in truth we have no means of fixing a scale for such valuations. We know that there are suns hundreds, even thousands, of times larger than the sun. Why should there not be others larger still in a similar proportion? *Non est naturæ mensura hominis electio*, Kepler wrote to Herwart in 1599. Our estimates are, in many cases, minimum values; we can place no upper limit to the vastness of the orbs of space. It is only safe to affirm that the greatest and the least of them are associated and conjoined in the immense aggregations of "this gorgeous arch, with golden worlds inlaid, built with Divine ambition."

The sidereal tribes are very differently affected towards the central plane of the system. Some, as it were, deliberately withdraw from it; others are exclusive in their preference for it; many press towards it, while maintaining a cosmo-

[1] Burns, *Knowledge*, vol. xxii. p. 227.
[2] *Ibid.* vol. xix. p. 205.

politan status. That white stars largely preponderate in the Milky Way, is a fact made evident by Kapteyn's discussion of the Cape Durchmusterung photographs.[1] It might, nevertheless, as Mr. Monck of Dublin first noted, be due to their superior areal brilliancy, which would cause them, with increase of distance, to come into view preferentially, and at last exclusively. The percentage of white stars must, indeed, apart from very unlikely specialties of distribution, augment among the lower magnitudes, since a star emitting light of the Sirian quality would appear equally bright when fully twice as far off as one of the same size clothed with a solar atmosphere. Moreover, Kapteyn's researches did not extend below the tenth magnitude, and the genuine galactic particles are of much lower grades of brightness. So that the nature of their spectra has not, up to the present, been disclosed to us. Yet a surmise regarding it may be hazarded. Mr. McClean perceived the bright helium stars included in his survey to be disproportionately numerous in the Milky Way zone. This is probably one among several symptoms of their great remoteness. They are sufficiently removed, perhaps, from the centre of the sidereal sphere to come within the sweep of the current of tendency setting in towards its equatorial regions. Now it seems probable that fainter specimens of the type are similarly, but more strongly condensed; and a further step on the tempting road of conjecture leads us to the inference that the dim aggregations girdling the heavens are mainly composed of stars of the Orion family—of stars reversing the duplicate series of hydrogen lines, besides those of oxygen, helium, nitrogen, and silicon.

We have seen in an earlier chapter that the Milky Way is the chosen resort of Wolf-Rayet stars. They doubtless belong to it intimately and entirely; and the same may be said of Novæ. This involves the strange consequence that, amid the radiant galactic hordes, there must circulate a multitude of large obscure bodies, fitted on occasion to blaze into sudden conflagration, on a scale startling to intelligent beholders in every quarter of the universe. Must we then conclude that dark stars are relatively more plentiful in the Milky Way than elsewhere? Not necessarily, perhaps, for its scarcely in-

[1] *Annals of Cape Observatory*, vol. iii. p. 22 (Introduction).

fringed monopoly in the production of temporary stars might be explained equally well by the virtual limitation to it of the conditions needed for luminous explosions, as by the abundance in it of their appropriate fuel.

Very few gaseous nebulæ have any considerable galactic latitude; they are characteristically Milky Way objects. There are, indeed, exceptions. Some noted planetaries—those in Draco and Ursa Major for example—are situated far outside the zone of concentration, and they present the appearance of being nearer to the earth than most members of the class. The "stellar" variety, on the other hand, which are presumably small through remoteness, are, to the best of our knowledge, limited to the Milky Way; while irregular nebulæ occur either in the main stream or in some of its affluents. Among these the Magellanic Clouds are, in a sense, to be counted, though they should rather be described as pools, left behind as the waters contracted into their present bed. They are composed, like the Milky Way, of mixed ingredients, stellar and nebulous; they seem to reproduce its condition; they bear the same primitive stamp. Their globular shape, however, suggests an autonomous constitution, each being probably a self-regulated body; while the galactic aggregations may be supposed exempt from the efficient control of a central authority. Dr Russell's photographs disclosed spiral tendencies in the Nubeculæ,[1] destined perhaps to become more and more pronounced with time.

Through the agency of the portrait-lens and the sensitive plate, the nebulous affinities of the Milky Way have been more fully recognised than was possible by visual means alone. Several of Professor Barnard's pictures exhibit an intermixture of vaguely diffused lucid matter with layers of minute stars, especially in parts of Cygnus, Cepheus, Perseus, Monoceros, and Scorpio. We see, then, that the great cosmic zone is not only frequented by nebulous objects, but is nebulous in itself. Yet it seems to repel from it the multitude of white nebulæ which tend to collect about its poles. This, at least, is the law of their visual distribution; but the camera threatens to abrogate it. Dr. Max Wolf holds that the results of his preliminary photographic surveys prove nebulæ to be in

[1] *Knowledge*, vol. xiv. p. 51.

reality scattered pretty evenly over the heavens. Only their average brightness, he thinks, varies, the so-called "nebular regions" in Cetus and Virgo having acquired their reputation as such not because nebulæ are more numerous, but because they are there more conspicuous than in the intervening celestial tracts. The subject, in fact, of nebular distribution, which had been supposed practically disposed of, has been, by photographic explorations, reopened for fresh discussion.

The crowding of globular clusters upon the Milky Way is unmistakable; and the inwardness of their relation to its condensations is manifested by their avoidance of the vacuous rifts, and their adherence to the stream-lines of luminosity. Hence arises the logical necessity for their radical separation from white nebulæ, to which they seem, in most respects, so near akin that one might be led to believe mere difference of distance to occasion the distinction between resolvable and irresolvable objects. Only the opposite galactic proclivities of the two classes decisively place them apart.

Within sight of that ultimate problem, the structure of the sidereal universe, we pause. Our thoughts meet, but they cannot grapple with it; nor does it come within the scope of our present purpose to make the attempt. We must be content to register the marks of growth and change legible in the Milky Way; to note the evidence of its comparatively recent origin and inchoate state; to avow our impotence to comprehend the Supreme design which it is directed to realise; and to bend in awe and admiration before the unfathomable depths of difficulty and mystery towards which the study of sidereal development, in its larger bearings, inevitably leads. *Die Schöpfung,* as Kant discerned, *ist niemals vollendet. Sie hat zwar einmal angefangen, aber sie wird niemals aufhören.*

# APPENDIX

## TABLE I

### Stars with Variable Spectra

| Name of Star. | Mag. | Position, 1900. | | Remarks. |
|---|---|---|---|---|
| | | R. A. | Dec. | |
| | | h. m. | | |
| $\gamma$ Cassiopeiæ . | 2·3 | 0 51 | +60° 10′ | H$\alpha$ usually brilliant; at times invisible. $D_3$ intermittently bright. Further variations apparent. |
| 8 Schjellerup . | 7·2 | 1 12 | +47° 9′ | Spectrum continuous, 14th November 1887; fluted, 6th October 1891. |
| *o* Ceti . . | var. | 2 14 | − 3° 26′ | H$\gamma$ and H$\delta$ triple, 29th August; single, 6th November 1898. Iron (?) line at $\lambda$ 4808, dark at maxima of 1896 and 1897, bright in 1898. |
| $\psi$ Persei . . | 4·2 | 3 29 | +47° 52′ | Bright H$\beta$ shifts capriciously from one to the other side of a broad absorption-band, on which it is normally central (A. C. Maury). |
| 11 Monocerotis . | 4·7 | 6 24 | − 6° 58′ | Bright H$\beta$ less refrangible in 1888-90, more refrangible in 1891-2 than dark H$\beta$. |
| A.G.C. 9181 . | 5·4 | 7 10 | −26° 10′ | H$\beta$ and H$\gamma$ vary from dark to bright, not always in concert (A. J. Cannon). |
| J Velorum . | 4·4 | 10 17 | −55° 33′ | H$\beta$ and H$\gamma$ intermittently bright (A. J. Cannon). |
| A.G.C. 14,686 . | 7·0 | 10 40 | −59° 1′ | H-lines alternately bright and dark (*Harvard Circular*, No. 32). |
| $\eta$ Centauri. . | 2·5 | 14 29 | −41° 43′ | Composite spectrum, subject to intricate changes, partly explicable by relative motion-shifts of bright and dark H$\beta$ (A. J. Cannon). |
| $\kappa'$ Apodis . . | 5·6 | 15 21 | −73° 2′ | H$\beta$ variably bright (A. J. Cannon). |
| R Coronæ . . | var. | 15 44 | +28° 28′ | Spectrum at times continuous, at times banded. Bright lines occasionally visible. |

| Name of Star. | Mag. | Position, 1900. R. A. | Position, 1900. Dec. | Remarks. |
|---|---|---|---|---|
| | | h. m. | | |
| 214 Schjellerup | 7·0 | 18 28 | − 5° 18′ | Spectrum third type, 1880; second type, 1892. |
| R Scuti | var. | 18 42 | − 5° 49′ | Type III.; bands effaced at maxima. Unidentified bright lines recorded by Espin in 1890. |
| $\beta$ Lyræ | var. | 18 46 | +33° 15′ | Composite spectra with variable and shifting bright lines. |
| $\upsilon$ Sagitarii | 4·7 | 19 16 | −16° 8′ | H$\beta$ variably bright (A. C. Maury). |
| $\epsilon$ Capricorni | 4·5 | 21 36 | −19° 54′ | Composite helium spectrum. Changes possibly explicable by motion-shifts of two dissimilar sets of dark lines (A. J. Cannon). |

## TABLE II

### List of Spectroscopic Binaries

| Name of Star. | R. A. 1900. | Dec. 1900. | Mag. | Period in Days. | Remarks. |
|---|---|---|---|---|---|
| | h. m. | | | | |
| $\eta$ Andromedæ. | 0 52 | +22° 52′ | 4·6 | ... | Variable radial motion discovered by Campbell, 1900. Spectrum of companion faintly visible. Solar type. |
| Polaris | 1 22 | +88° 46′ | 2·1 | 3·97 | Variable velocity detected by Campbell, 1899. Spectrum early solar. Companion dark. Further disturbance indicated. |
| $\phi$ Persei | 1 37·4 | +50° 11′ | 4·2 | ... | Variable velocity detected by Campbell in 1902. Bright-line helium spectrum. |
| $\xi$ Piscium | 1 48 | + 2° 42′ | 4·7 | ... | Variable velocity discovered by Campbell, 1900. Companion sensibly dark. |
| $\xi_1$ Ceti | 2 8 | + 8° 23′ | 4·4 | ... | Variable velocity discovered by Campbell, October 1900. Companion dark. |
| 12 Persei | 2 36 | +39° 46′ | 4·9 | ... | Discovered by Campbell, January 1900. Two similar spectra visible at elongations. |
| $\tau$ Persei | 2 47 | +52° 22′ | 4·0 | ... | Radial velocity found variable by Campbell in October 1900. Spectrum previously observed as composite by A. C. Maury. Solar type. |
| $\beta$ Persei (Algol) | 3 2 | +40° 34′ | var. | 2·87 | Alternations of approach and recession discovered by Vogel, 1889. Companion obscure. |

| Name of Star. | R. A. 1900. | Dec. 1900. | Mag. | Period in Days. | Remarks. |
|---|---|---|---|---|---|
| | h. m. | | | | |
| *o* Persei . . | 3 38 | +31° 58′ | 4·0 | ... | Found by W. S. Adams in 1902 to vary in radial velocity to the extent of 251 kil. Single spectrum of helium type. |
| λ Tauri . . | 3 55 | +12° 12′ | var. | 3·95 | Changes of velocity measured by Bélopolsky, 1897. Spectrum periodically double. Helium type. |
| α Aurigæ (Capella) | 5 9 | +45° 54′ | 0·2 | 104 | Discovered by Campbell and Newall, 1899. Spectrum composite. |
| η Orionis . | 5 19·4 | − 2° 29′ | 3·5 | ... | Variable velocity detected with the Bruce spectrograph in 1901 by W. S. Adams and E. B. Frost. |
| δ Orionis . | 5 27 | − 0° 22′ | 2·4 | 1·92 | Discovered by Deslandres, 1900. Spectrum of helium type. Companion obscure. |
| β Aurigæ . | 5 52 | +44° 56′ | 2·1 | 3·98 | Discovered by Miss Maury in 1889. Spectrum first type; doubled periodically. |
| η Geminorum . | 6 8·8 | +22° 33′ | 3·2 − 4·2 (period, 231ᵈ) | ... | Variable velocity detected by Campbell in 1902. Close visual companion discovered by Burnham, 1881. Slow revolution indicated. The variable shows a fluted spectrum. |
| ζ Geminorum . | 6 58 | +20° 48′ | var. | 10·15 | Discovered by Bélopolsky, 1898. Subordinate period of 8·38ᵈ detected by Campbell. Spectrum solar type. Companion dark. |
| γ Canis Minoris | 7 23 | + 9° 8′ | 4·6 | ... | Discovered by Campbell in 1902 to vary in velocity to the extent of 8 miles per second. |
| α′ Geminorum (Castor) | 7 28 | +32° 7′ | 2·0 | 2·95 | Discovered by Bélopolsky, 1896. First type spectrum. Companion obscure. Line of apsides found to revolve in 2100ᵈ. |
| V Puppis . | 7 55 | − 48° 58′ | var. | 1·45 | Periodical doubling of lines detected by Pickering from Arequipa plates in 1896. A. W. Roberts finds components to revolve in contact. Helium spectrum. |
| ε Hydræ . | 8 42 | + 6° 48′ | 3·6 | ... | Variable velocity detected by Campbell, December 1900. Solar spectrum. |
| *o* Leonis . . | 9 36 | +10° 21′ | 3·8 | 14·5 | Discovered by Campbell, 1898. Spectrum previously noticed by Miss Maury to be compounded of two varieties of the Sirian type. |
| ξ Ursæ Majoris | 11 13 | +32° 6′ | 3·8 | ... | Principal component of visual binary found by Wright in 1900 to be spectroscopically double. Spectrum solar. |
| 93 Leonis . . | 11 43 | +20° 46′ | 4·6 | ... | Variable velocity detected by Campbell, 1900. |

| Name of Star. | R. A. 1900. | Dec. 1900. | Mag. | Period in Days. | Remarks. |
|---|---|---|---|---|---|
| | h. m. | | | | |
| ζ Ursæ Majoris | 13 20 | +55° 27′ | 2·4 | 20·6 | Discovered by Pickering, 1889. Period fixed by Vogel, 1901. Spectrum advanced helium type. Components equally bright. |
| α Virginis . | 13 20 | −10° 38′ | 1·2 | 4·0 | Discovered by Vogel, 1890. Companion faintly luminous. Helium spectrum. |
| ζ Centuari . | 13 49 | −46° 47′ | 2·8 | 8·02 | Discovered by Mrs. Fleming, 1890. Components unequally bright. Spectrum helium type. |
| d Boötis . . | 14 6 | +25° 34′ | 4·8 | ... | Variable velocity discovered by Wright, April 1900. |
| β Lupi . . | 14 52 | −42° 44′ | 2·7 | ... | Discovered by Mrs. Fleming, 1897. Components equally luminous. Helium spectrum. |
| δ Libræ . . | 14 56 | − 8° 8′ | var. | 2·33 | Variable velocity detected by Adams, 1902. Spectrum advanced helium type. |
| ε Libræ . . | 15 19 | − 9° 57′ | 5·2 | 90+ | Discovered by Campbell, 1899. Solar spectrum. Companion obscure. |
| π Scorpii . . | 15 53 | −25° 49′ | 3·1 | 1·57 | Discovered by Miss Cannon, 1899. Helium spectrum. Components unequally bright. |
| θ Draconis . | 16 0 | +58° 50′ | 4·2 | 9 | Discovered by Campbell, 1899. Spectrum solar type. Companion obscure. |
| β Herculis . | 16 26 | +21° 42′ | 2·8 | ... | Variable velocity detected by Campbell, 1899. Companion dark. Arcturian spectrum. |
| $\mu_1$ Scorpii . . | 16 45 | −37° 53′ | 3·3 | 1·45 | Discovered by Bailey, 1896. Components unequally bright, perhaps variable. Spectra of helium type. |
| h Draconis . | 16 55 | +65° 17′ | 4·7 | ... | Variable velocity detected by Campbell, 1899. Early solar spectrum. Companion dark. |
| ε Ursæ Minoris | 16 56 | +82° 12′ | 4·5 | ... | Discovered by Campbell, 1899. Spectrum solar. Companion obscure. |
| ω Draconis . | 17 38 | +68° 48′ | 4·9 | ... | Discovered by Campbell, 1899. Spectrum solar. Companion obscure. |
| χ Draconis . | 18 23 | +72° 42′ | 3·7 | 282 | Variable velocity detected by Campbell, 1898. Period computed by Wright. Early solar spectrum. Companion dark. |
| 2 Scuti . . | 18 37 | − 9° 9′ | 4·8 | ... | Variable velocity detected by Wright, 1900. Companion dark. |
| β Scuti . . | 18 42 | − 4° 51′ | 4·4 | ... | Variable velocity detected by Wright, 1900. Companion obscure. |

| Name of Star. | R. A. 1900. | Dec. 1900. | Mag. | Period in Days. | Remarks. |
|---|---|---|---|---|---|
| | h. m. | | | | |
| $\beta$ Lyræ . . | 18 46 | +33° 15′ | var. | 12·91 | Binary character discovered by Pickering, 1891. Bright-line helium spectrum. Components luminous. |
| 113 Herculis . | 18 50 | +22° 32′ | 4·6 | ... | Variable velocity detected by Wright, July 1900. Companion obscure. |
| $\upsilon$ Sagittarii . | 19 16 | −16° 8′ | 4·7 | ... | Variable velocity discovered by Campbell, 1899. Spectrum noted as composite by Miss Maury. Of helium type with bright lines. |
| $\eta$ Aquilæ . | 19 47 | + 0° 45′ | var. | 7·18 | Variable velocity detected by Bélopolsky, 1895. Spectrum solar. Companion dark. |
| $o_1$ Cygni . . | 20 10 | +46° 26′ | 3·8 | ... | Variable velocity detected by Campbell, July 1900. Spectrum previously described by Miss Maury as including Sirian and solar ingredients. |
| $\beta$ Capricorni . | 20 15 | −15° 5′ | 3·4 | ... | Variable velocity detected by Campbell, 1899. Spectrum previously perceived by Miss Maury to be of Sirian and solar composition. |
| $\alpha$ Equulei . | 21 11 | + 4° 50′ | 4·1 | ... | Variable velocity to the extent of 15 miles a second discovered by Campbell in 1902. Miss Maury had recorded a composite spectrum, solar and Sirian. |
| $\kappa$ Pegasi . . | 21 40 | +25° 11′ | 4·2 | 6± | Smaller member of the visual binary found by Campbell in 1900 to be in rapid revolution round a dark companion. Sirian spectrum. |
| $\iota$ Pegasi . . | 22 2 | +24° 51′ | 4·0 | ... | Variable velocity detected by Campbell, 1898. Spectrum of Procyon class. Companion obscure. |
| $\delta$ Cephei . . | 22 25 | +57° 54′ | var. | 5·37 | Binary character discovered by Bélopolsky, 1894. Solar spectrum. Companion dark. |
| $\eta$ Pegasi . . | 22 38 | +29° 42′ | 3·1 | 818·0 | Variable velocity detected by Campbell, 1898. Spectrum solar. Companion dark. |
| $o$ Andromedæ . | 22 57 | +41° 47′ | 3·8 | ... | Variable velocity detected by Campbell, 1902. Composite spectrum—Sirian and Orion—recorded by Miss Maury. |
| $\pi$ Cephei . . | 23 5 | +74° 51′ | 4·5 | ... | Variable motion detected by Campbell, 1900. Companion dark. |
| $\lambda$ Andromedæ . | 23 33 | +45° 56′ | 4·0 | 19·2 | Variable motion detected by Campbell, 1890. Spectrum Arcturian. Companion dark. |

# INDEX

THE END

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